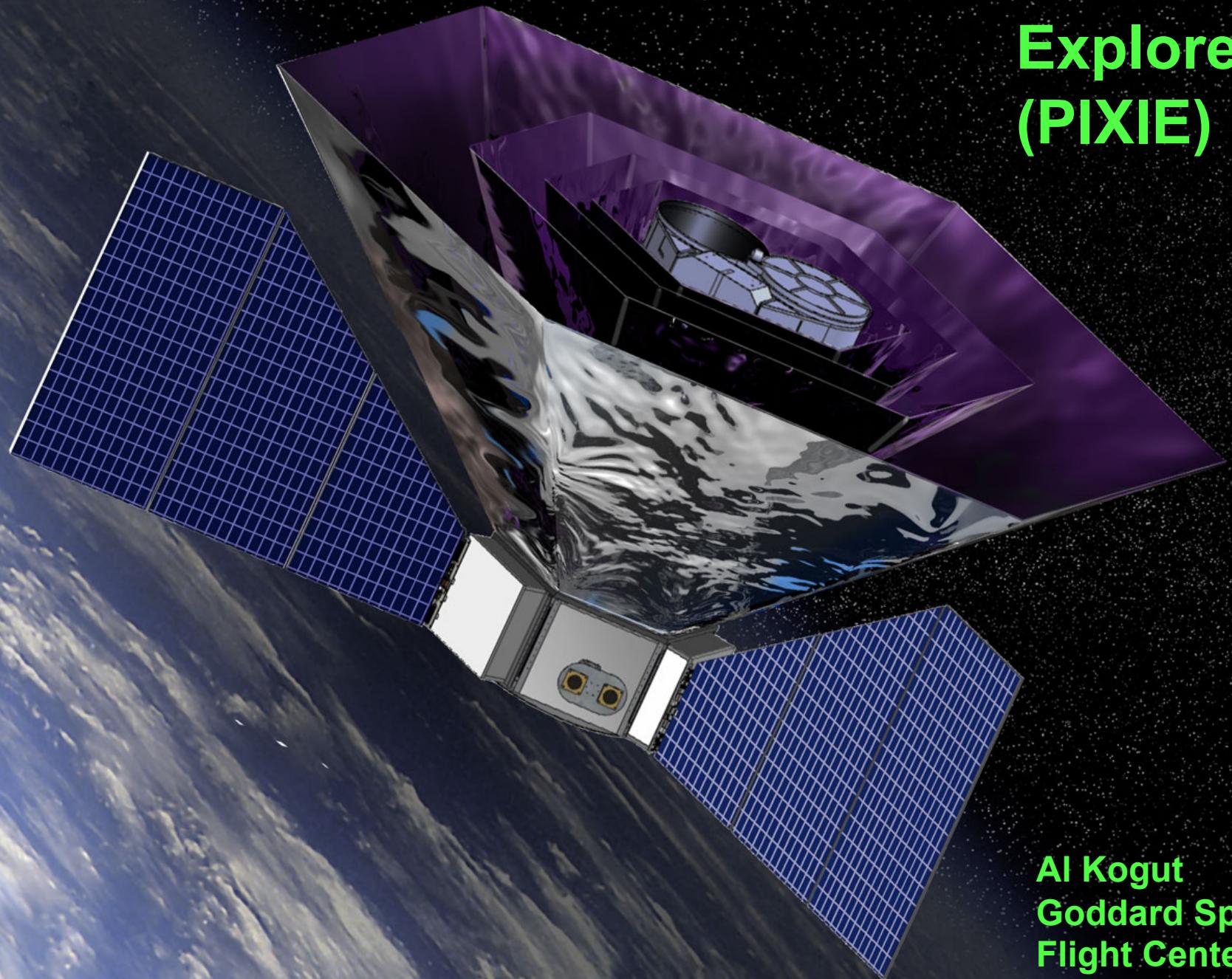
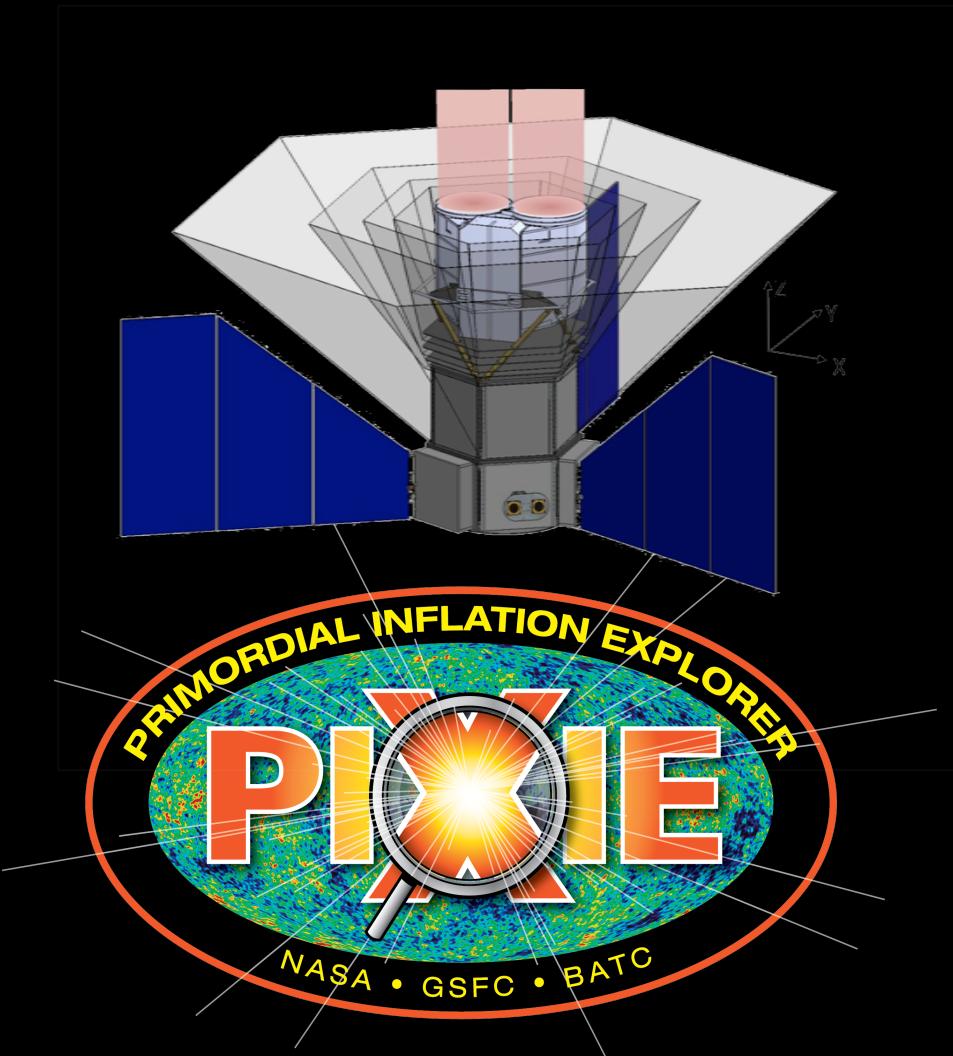


Primordial Inflation Explorer (PIXIE)



Al Kogut
Goddard Space
Flight Center

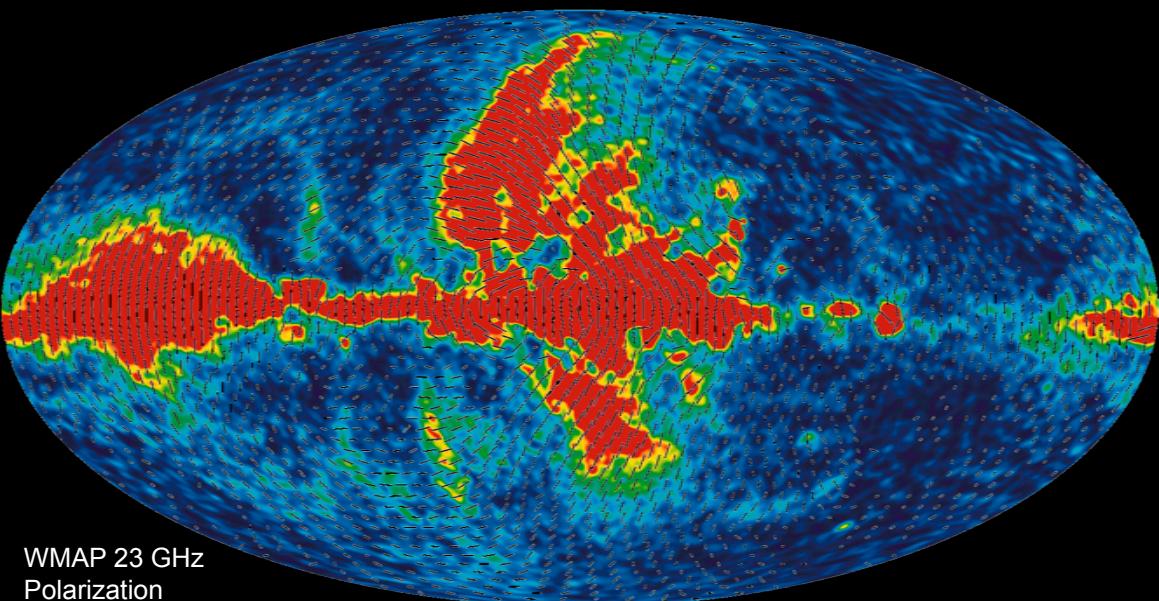
Primordial Inflation Explorer



Name	Role	Institution
A. Kogut	PI	GSFC
D. Fixsen	IS	UMD
D. Chuss	Co-I	GSFC
J. Dotson	Co-I	ARC
E. Dwek	Co-I	GSFC
M. Halpern	Co-I	UBC
G. Hinshaw	Co-I	UBC
S. Meyer	Co-I	U. Chicago
H. Moseley	Co-I	GSFC
M. Seiffert	Co-I	JPL
D. Spergel	Co-I	Princeton
E. Wollack	Co-I	GSFC

**Measure B-Mode Polarization
To Limits Imposed By Astrophysical and Cosmological Foregrounds**

B-Mode Fundamentals

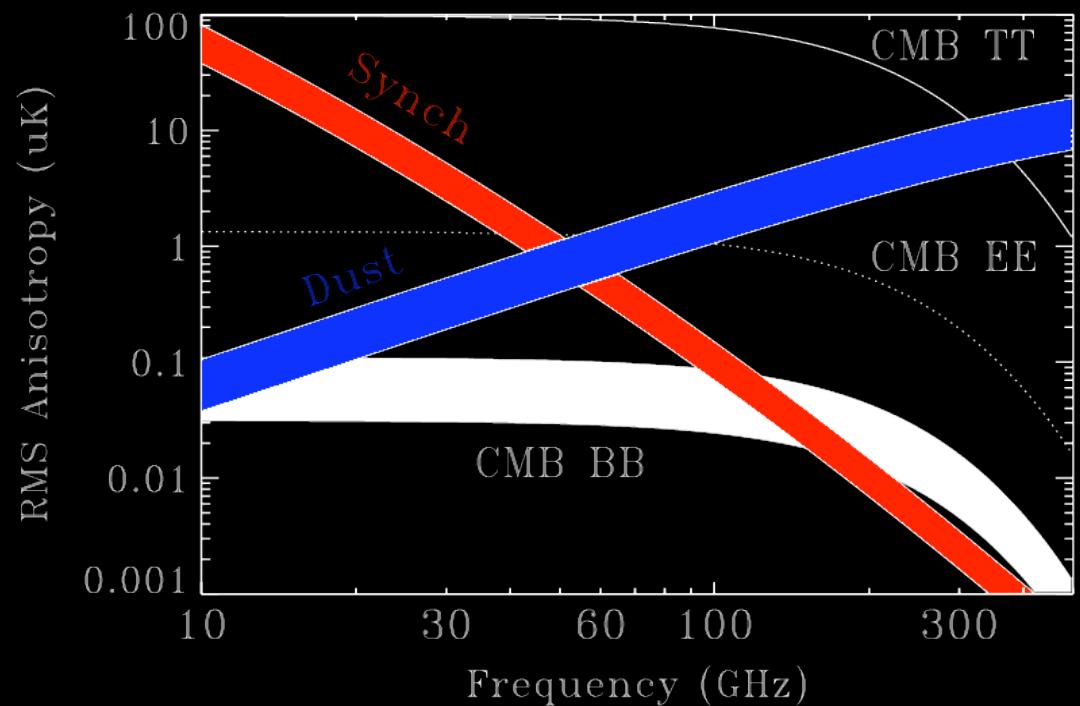


WMAP 23 GHz
Polarization

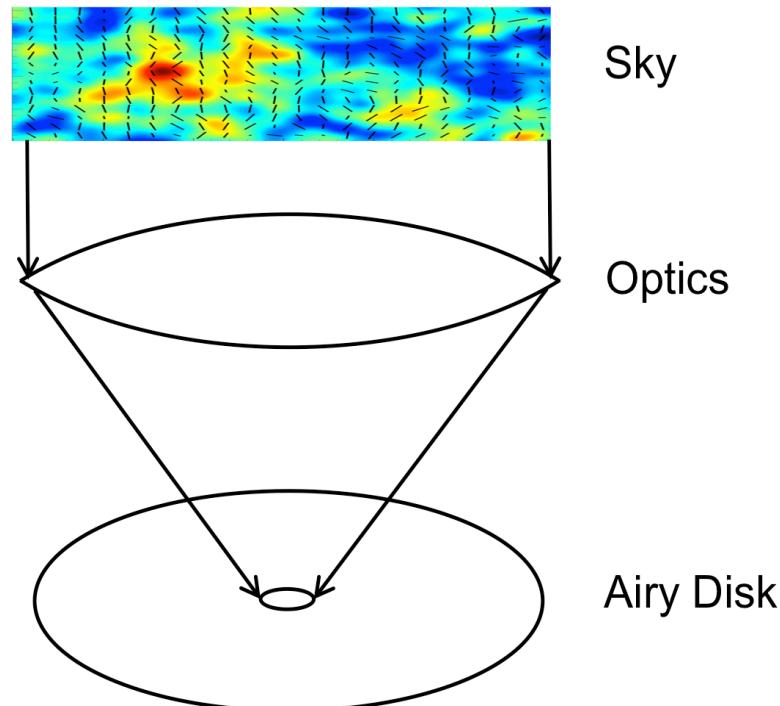
Signal is faint
Foregrounds are bright
Everything is confusing

Requirements for B-Mode Detection

- Sensitivity
- Foreground Subtraction
- Systematic Error Control



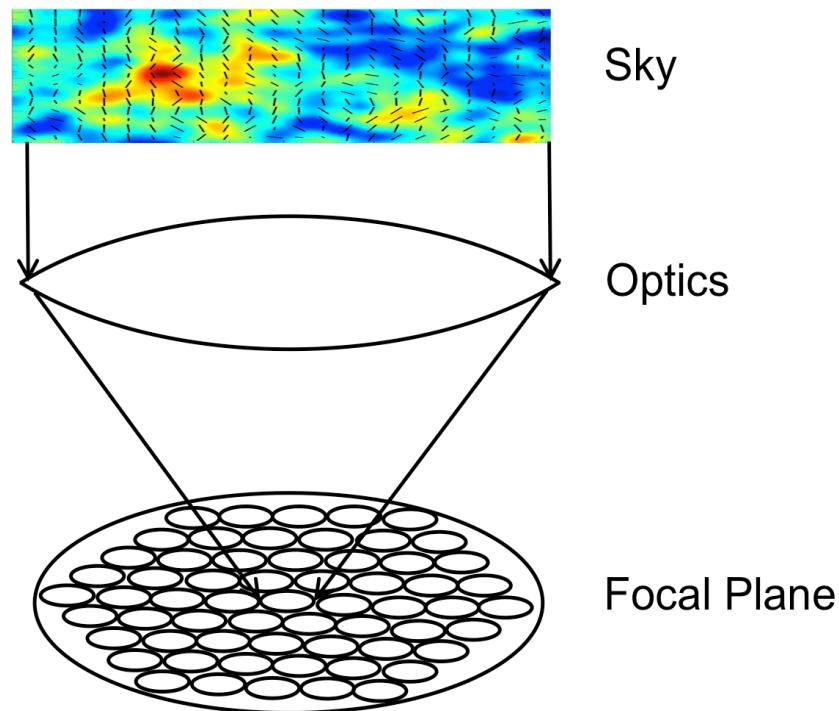
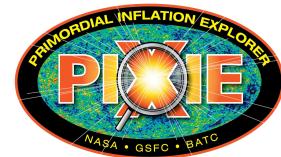
Optical Design for CMB



Conventional
Focal Plane

Single-Moded Pixel

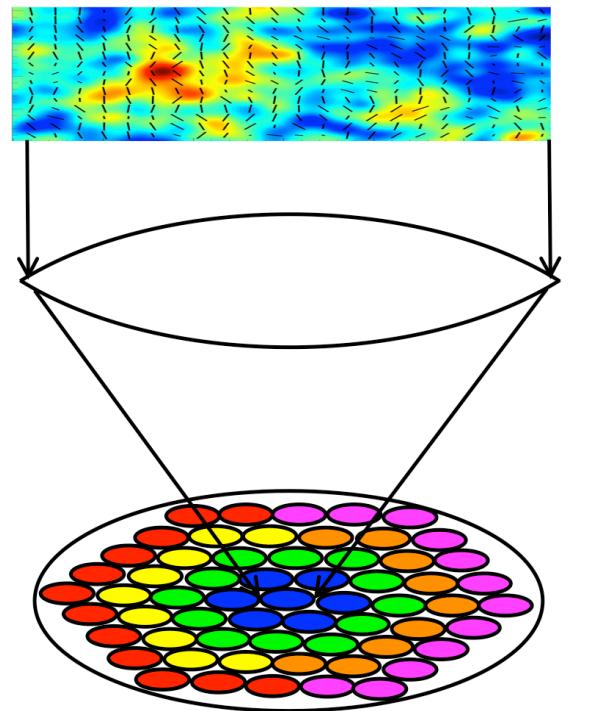
Optical Design for CMB



Conventional
Focal Plane

Photon Limit: Add Detectors

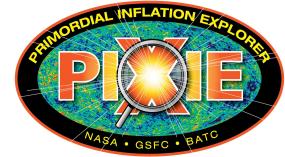
Optical Design for CMB



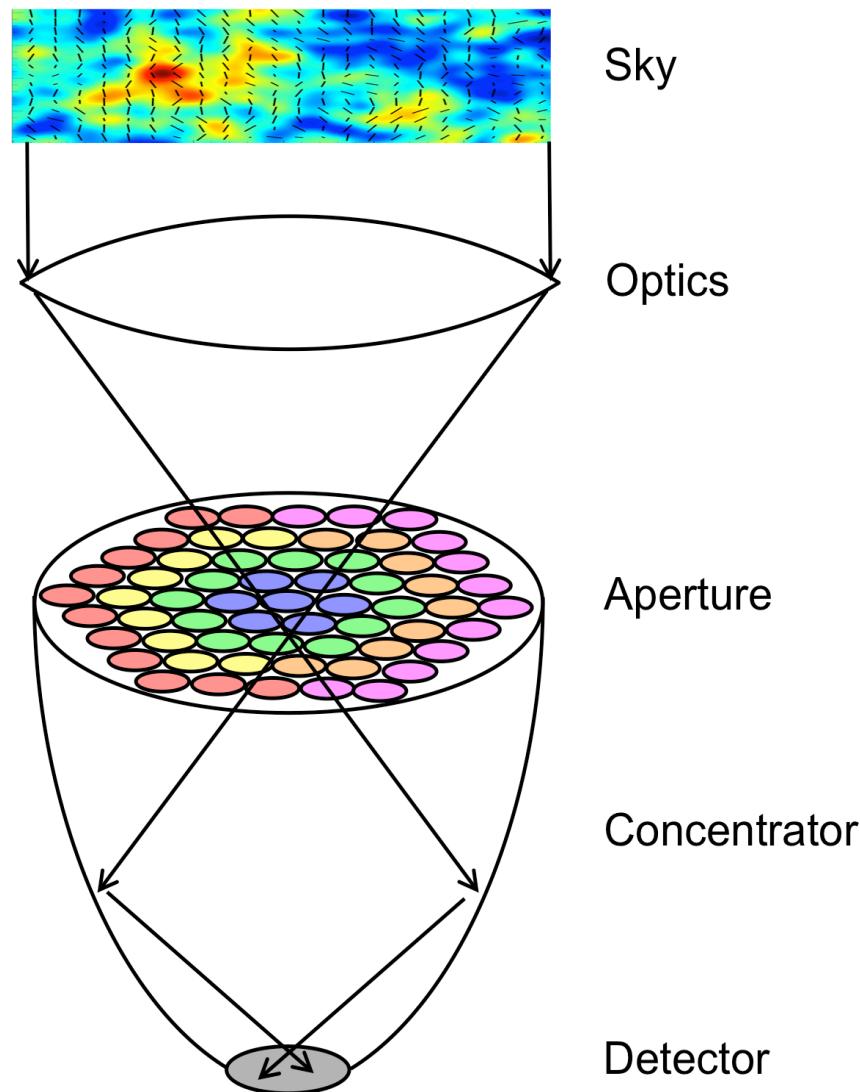
Conventional
Focal Plane

Foregrounds: Separate Bands

Problem: Getting enough sensitivity in enough frequency bands requires 10,000 background-limited detectors!



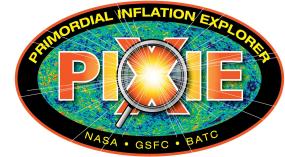
PIXIE Optical Solution



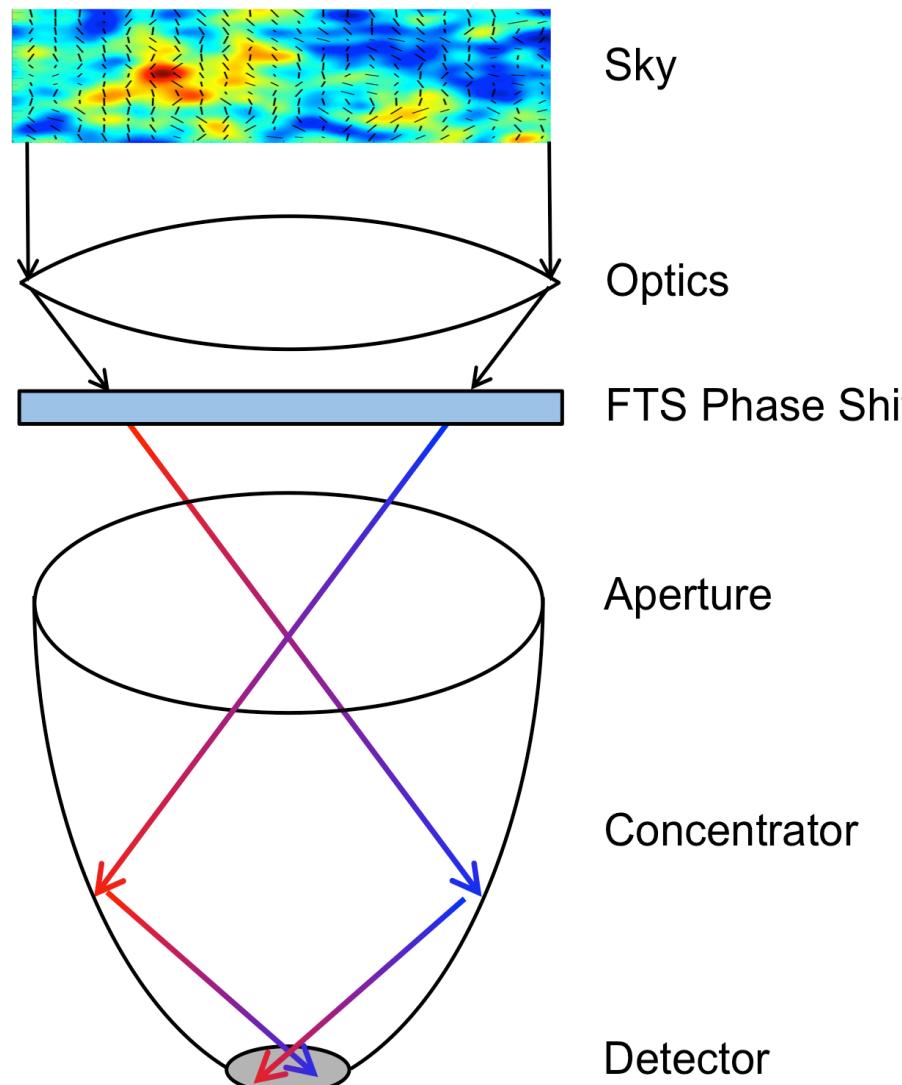
PIXIE

*Need more photons,
not more detectors!*

Replace tiled focal plane
with
multi-moded concentrator



PIXIE Optical Solution



PIXIE

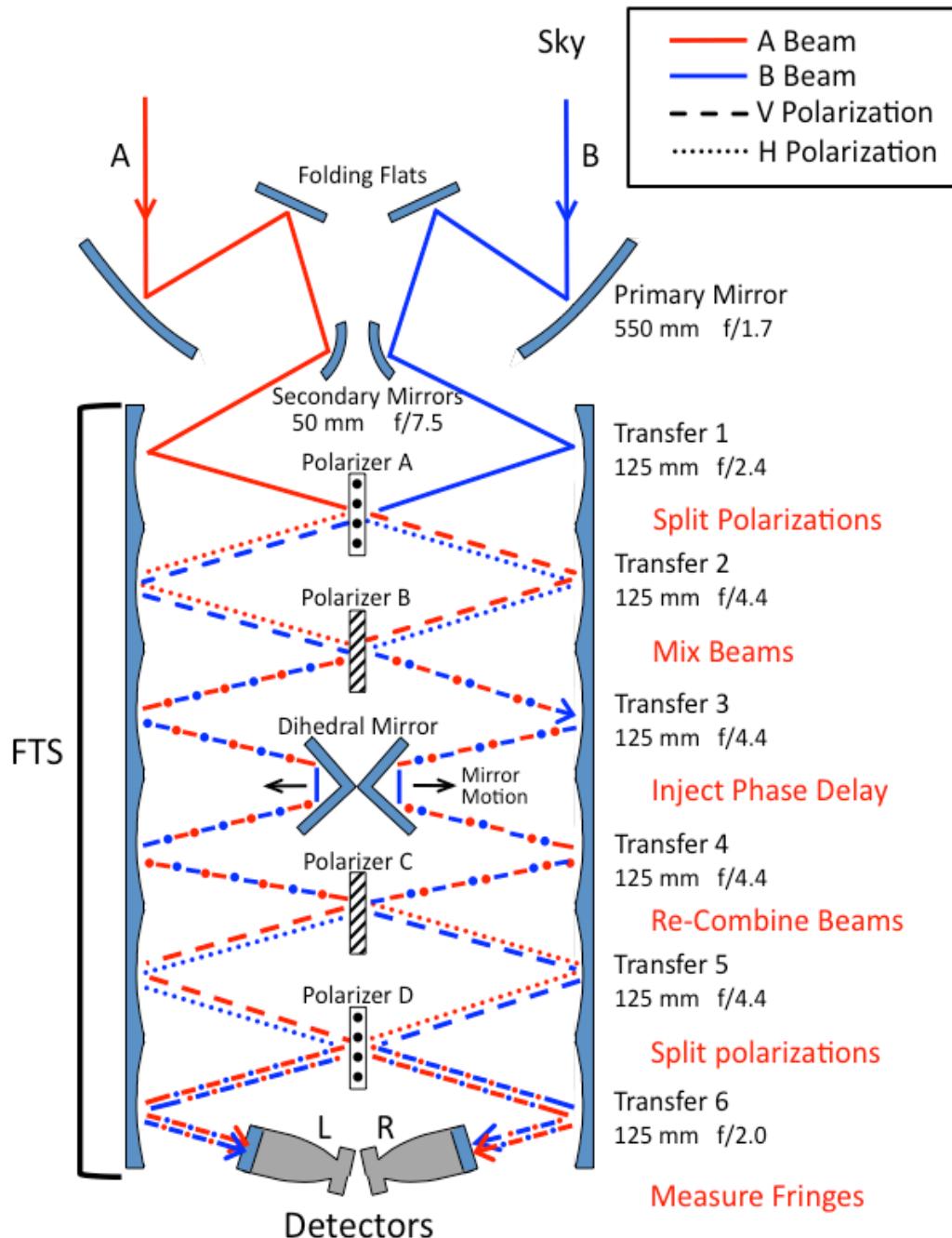
Replace multi-color detectors
with
Fourier transform spectrometer

Replace tiled focal plane
with
multi-moded concentrator

*Win-Win: Sensitivity and spectra
from a single detector*



PIXIE Nulling Polarimeter



**Measured Fringe Pattern
Samples Frequency Spectrum
of Polarized Sky Emission**

$$P_{Lx} = \frac{1}{2} \int (E_{Ay}^2 + E_{Bx}^2) + (E_{Bx}^2 - E_{Ay}^2) \cos(z\omega/c) d\omega$$

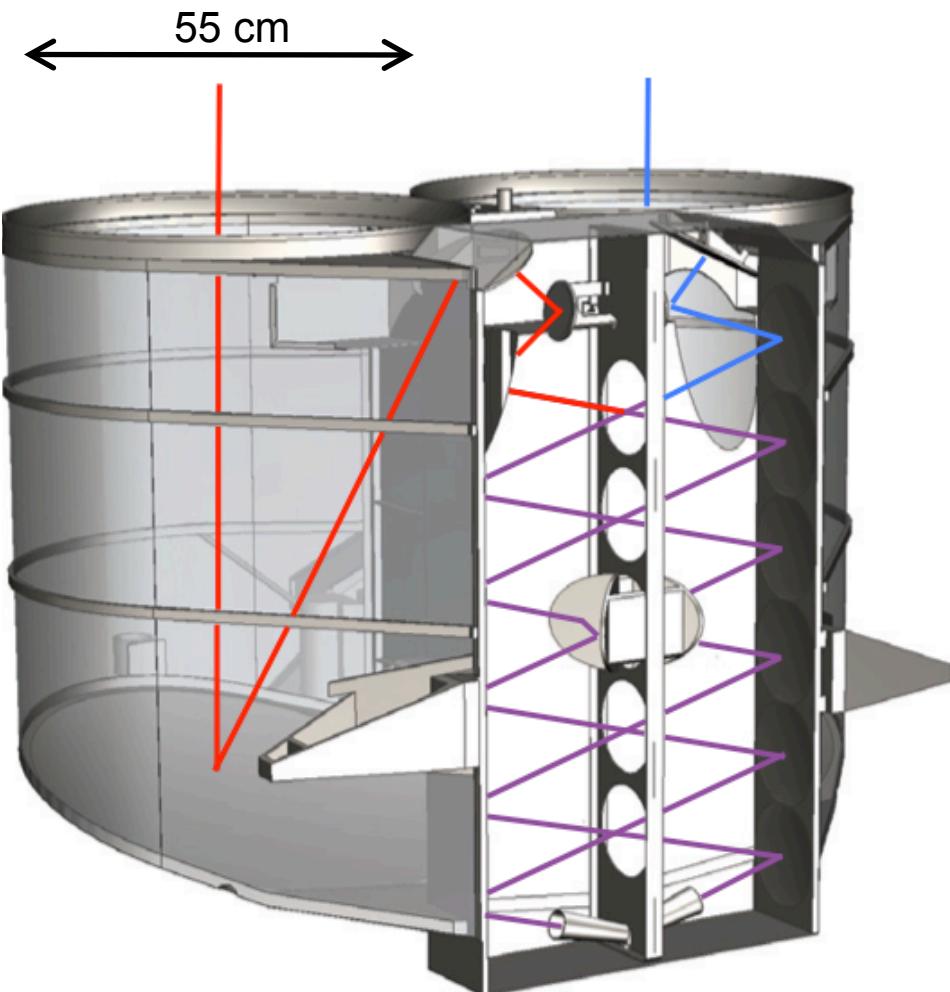
$$P_{Ly} = \frac{1}{2} \int (E_{Ax}^2 + E_{By}^2) + (E_{By}^2 - E_{Ax}^2) \cos(z\omega/c) d\omega$$

Stokes Q

Nulling Polarimeter: Zero = Zero

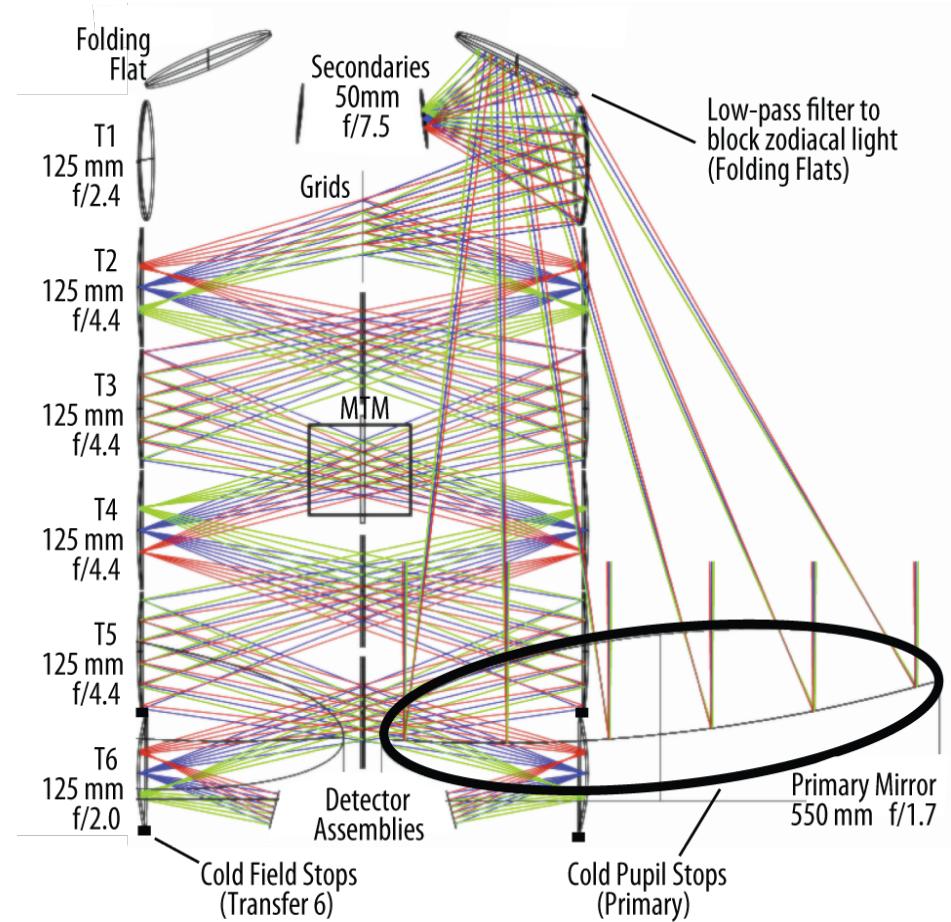


PIXIE Non-Imaging Optics



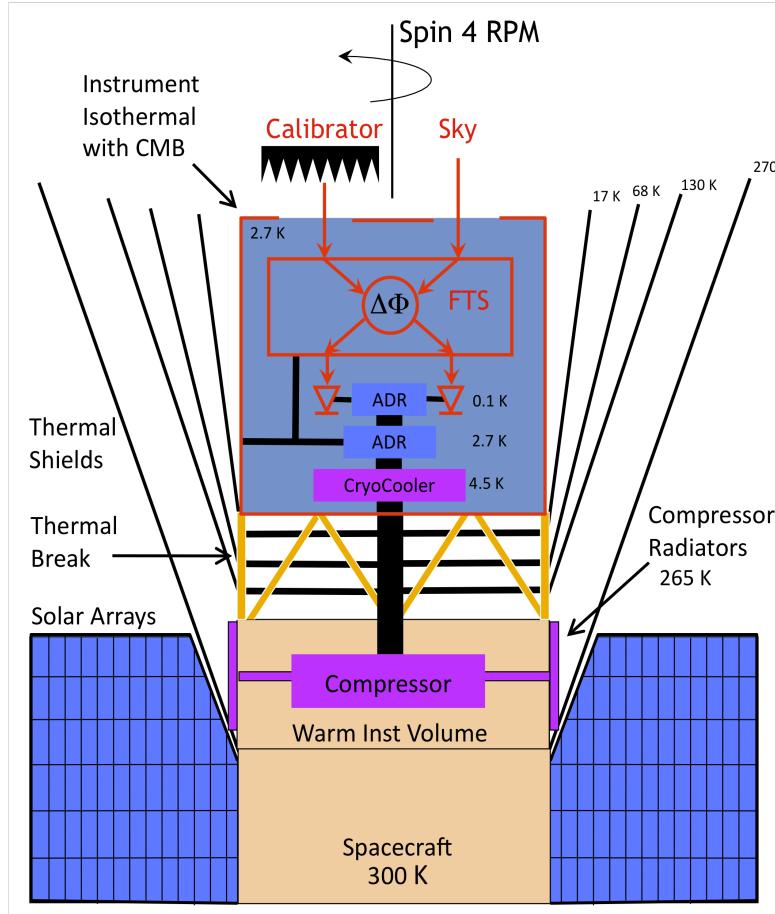
44,000 modes
on 4 detectors

Parameter	Value
Primary Mirror Diam	550 mm
Etendu	4 cm ² sr
Beam Diam	2.6° Tophat
Throughput	82%





Instrument Cryogenics



Fully cryogenic instrument

Cryo-cooler to 4.5 K

ADR to 2.7 K (instrument body)

ADR to 0.1 K (detectors)

Tolerant thermal design

Robust design/performance margins

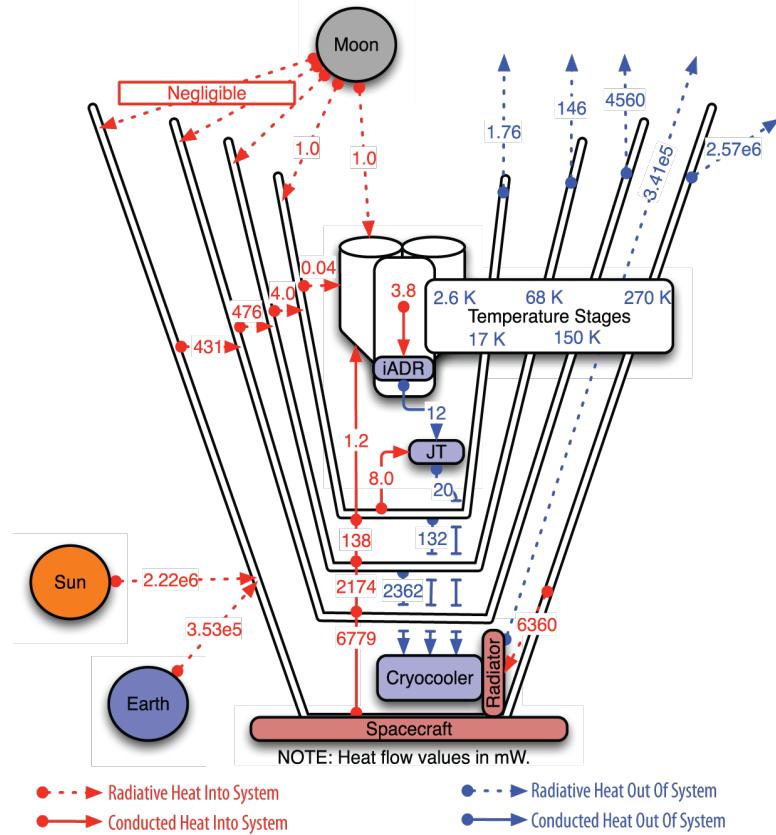
Active thermal control for all optical surfaces

Thermal "backbone" tolerant vs temperature excursions

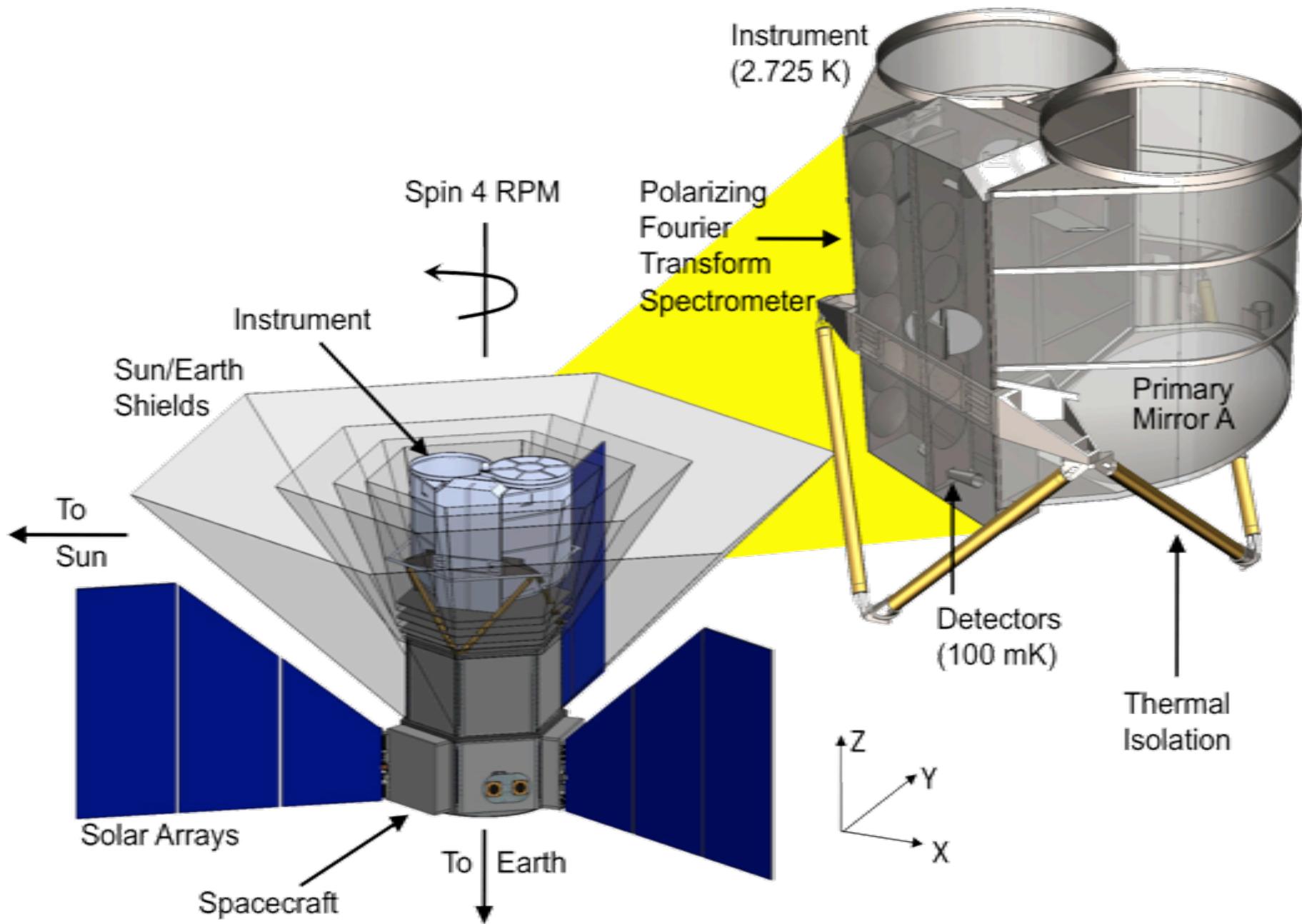
INSTRUMENT THERMAL LIFT BUDGET

Cooler Stage	Stage Temp (K)	CBE Loads (mW)	Derated Capability (mW)	Contingency & Margin (%)
Stirling (Upper Stage)	68	2362	4613	95%
Stirling (Lower Stage)	17	132	278	111%
Joule-Thomson	4.5	20	40	100%
iADR	2.6	6	12	100%
dADR	0.1	0.0014	0.03	2043%

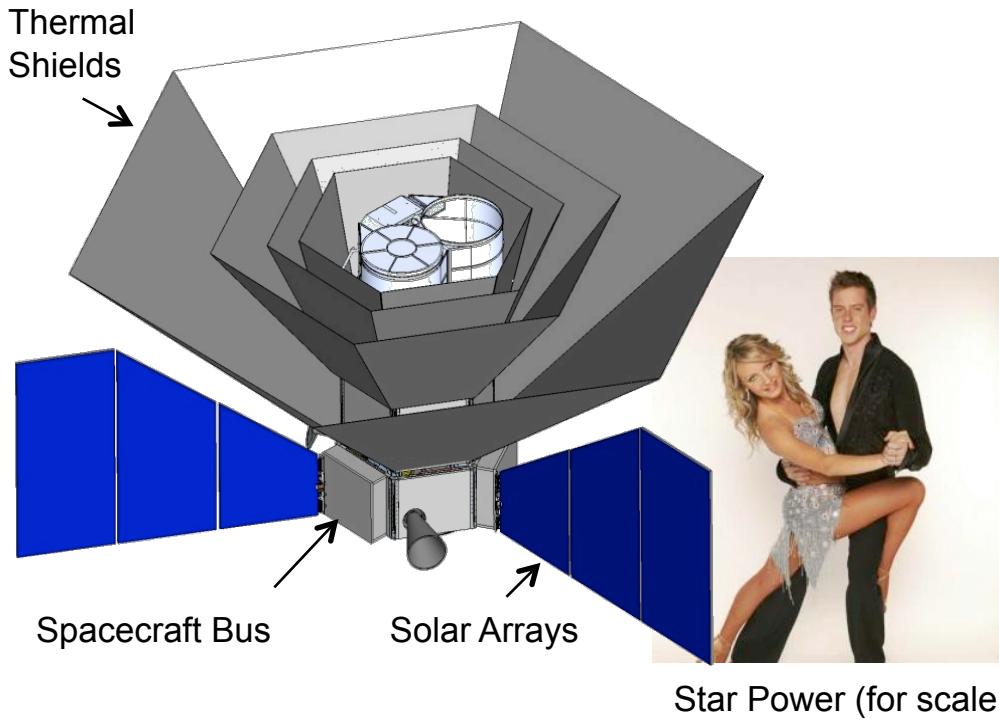
PIXIE INSTRUMENT HEAT FLOW



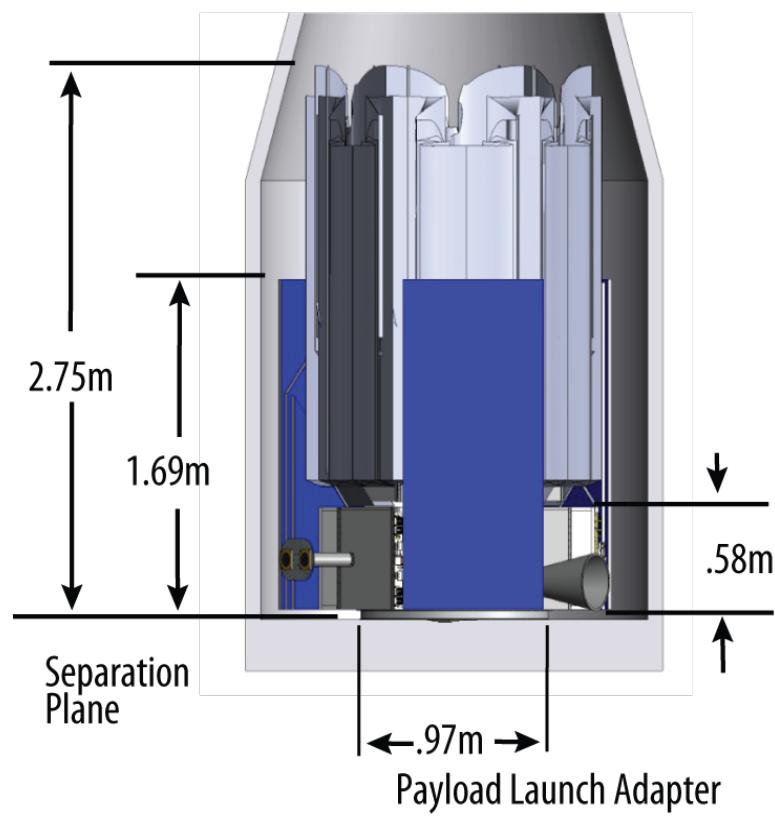
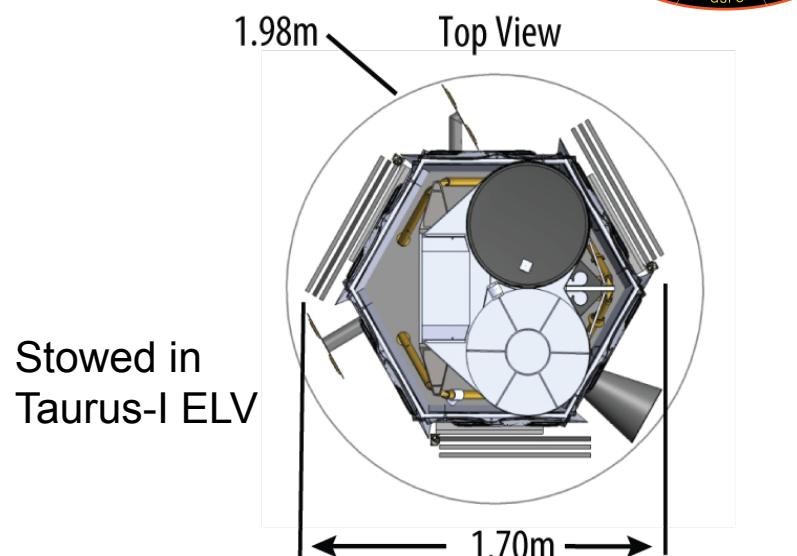
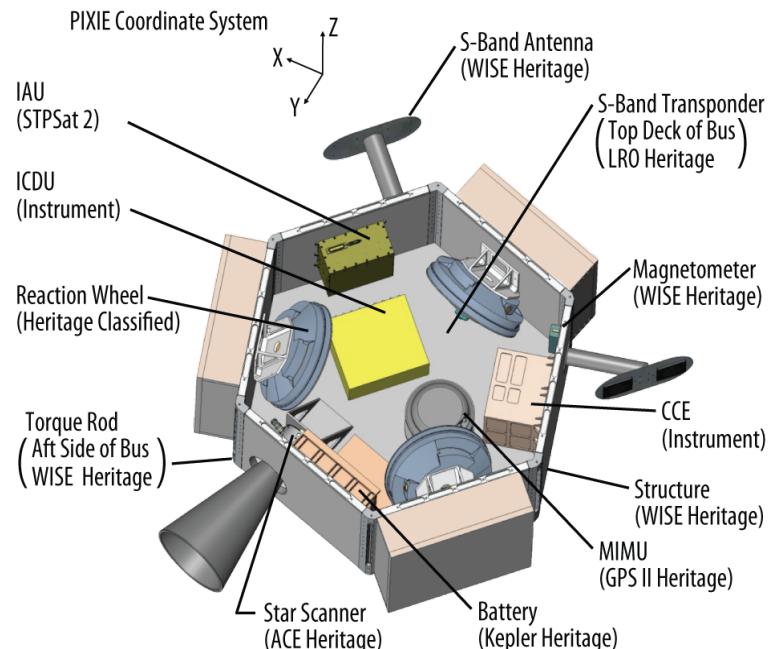
Instrument and Observatory



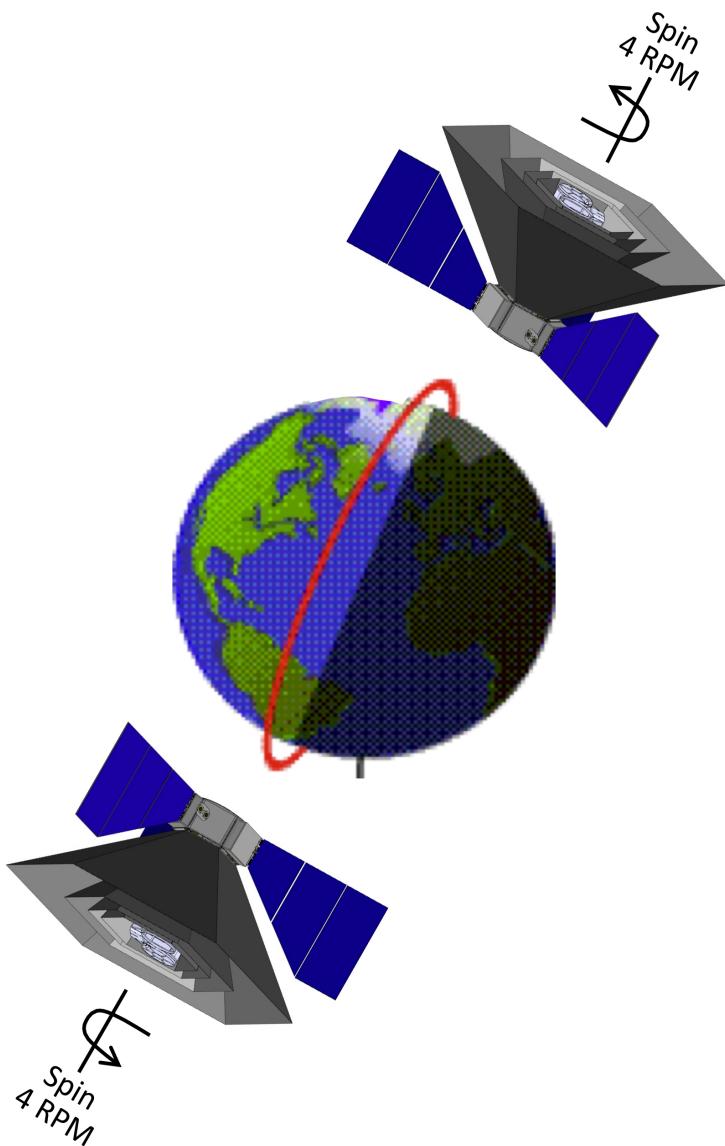
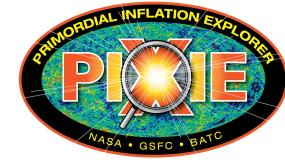
Observatory



Star Power (for scale)



PIXIE Mission Concept



Polar Sun-Synch Orbit

6 AM or 6 PM ascending node
660 km altitude

Like COBE, but lower

3-Axis Control

Spin at 4 RPM
Spin axis 90° to sun line
Zenith view (precess axis once/orbit)

COBE, WMAP

Routine Observations

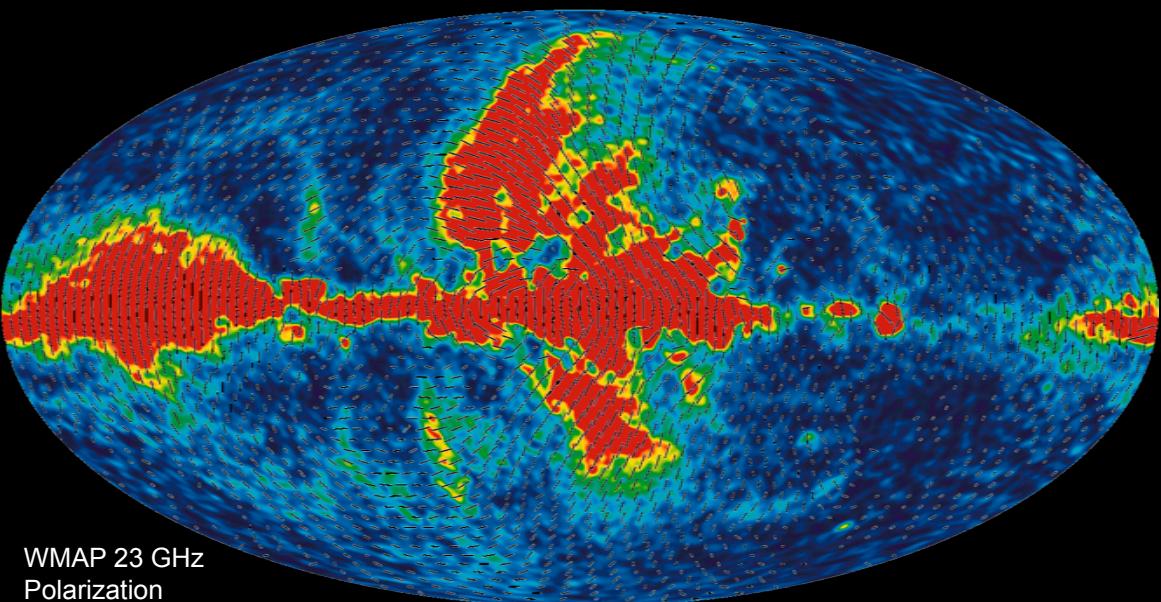
Spin and stare
Move calibrator every 2nd orbit
2 year baseline mission
4 year extended mission

COBE, WMAP, Planck

Small observatory fits multiple launch vehicles
Taurus-I ELV

Full-Sky Maps in Stokes IQU in 400 Channels 30 GHz to 6 THz

So What's The Problem?

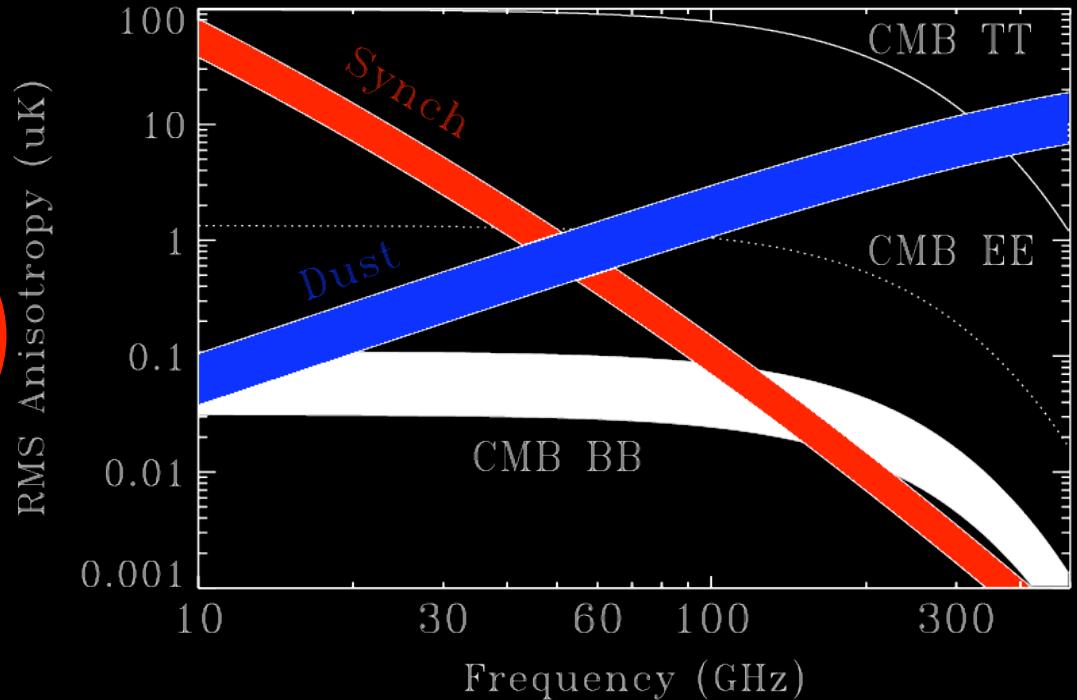


WMAP 23 GHz
Polarization

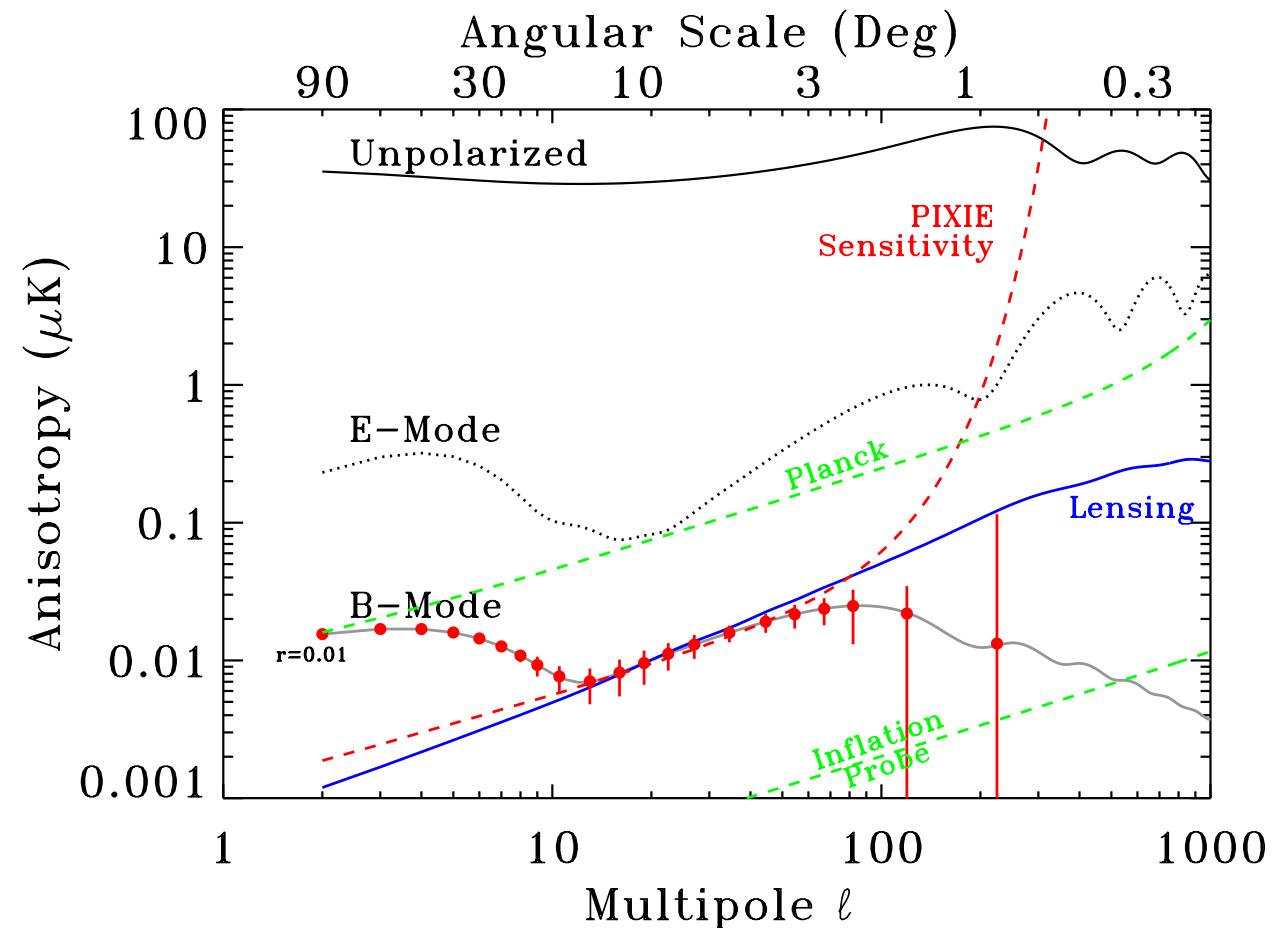
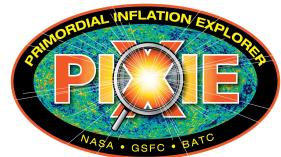
Signal is faint
Foregrounds are bright
Everything is confusing

Requirements for B-Mode Detection

- Sensitivity
- Foreground Subtraction
- Systematic Error Control



Sensitivity Matched to CMB Lensing



Full-sky maps in Stokes I, Q, U

NET = $13.6 \mu\text{K s}^{1/2}$ (Stokes I)

NEQ = $5.6 \mu\text{K s}^{1/2}$ (Stokes Q, U)

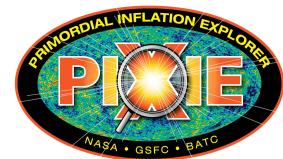
Beam independent of frequency

Tophat diameter 2.6° (FWHM $\sim 1.6^\circ$)

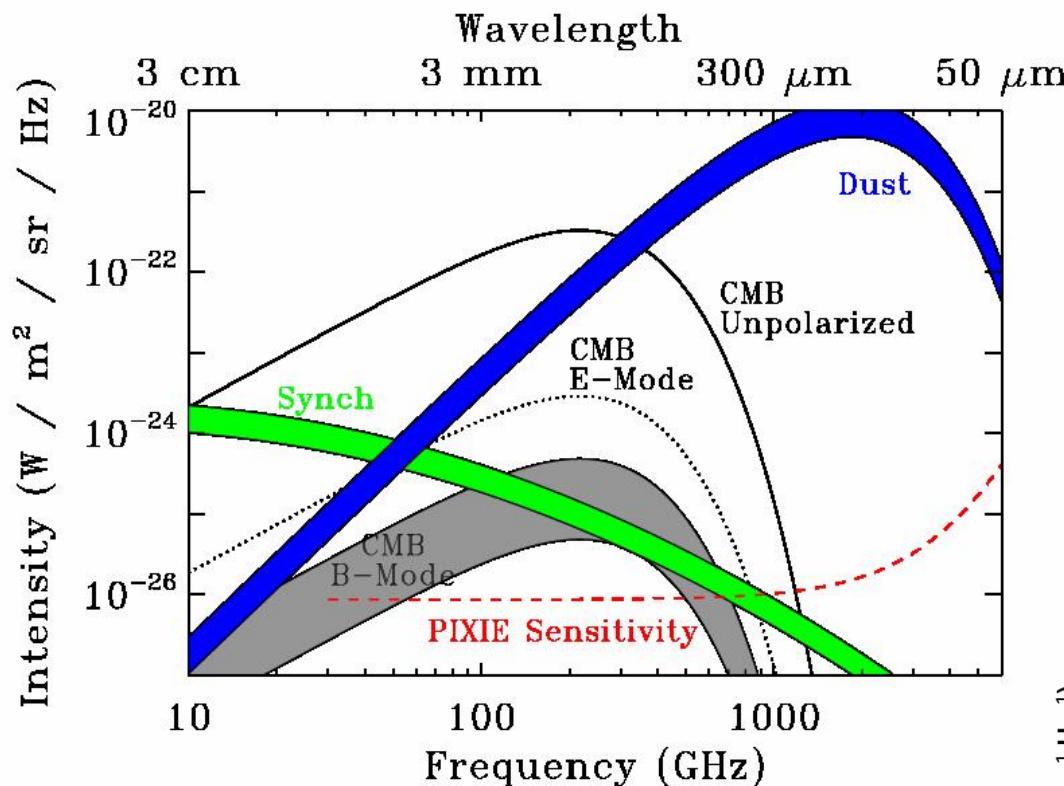
Multipoles $2 < \ell < 200$

Sensitivity 70 nK per $1^\circ \times 1^\circ$ pixel

B-mode limit $r < 0.001$ (5σ)



Foreground Subtraction

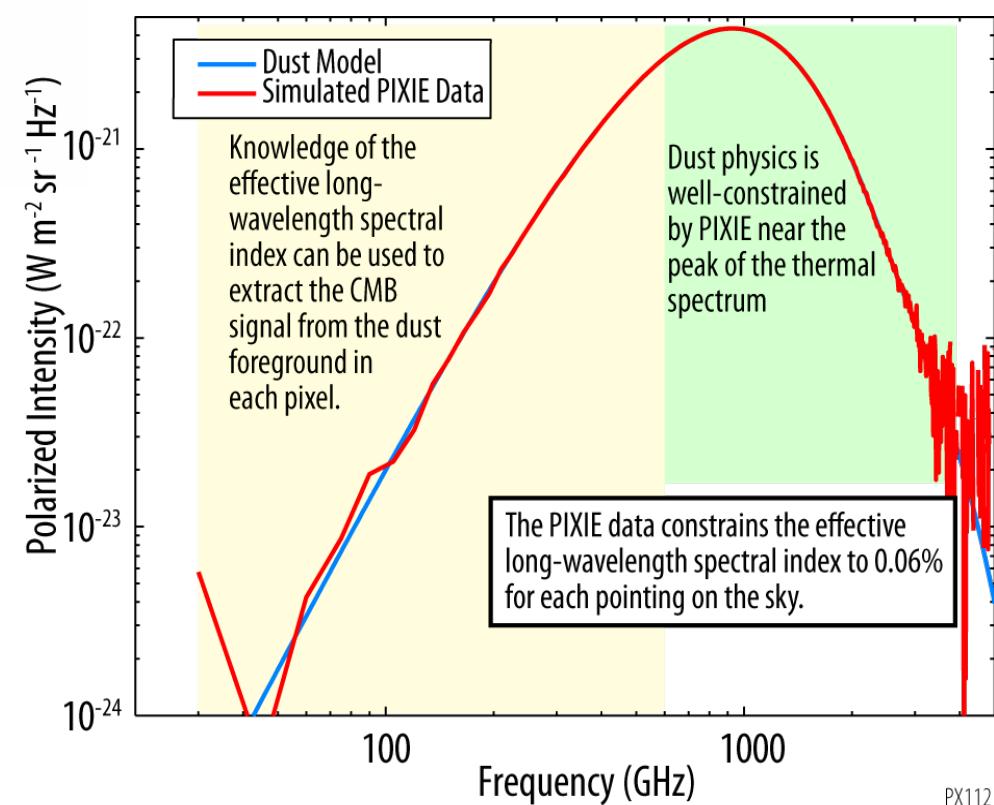


Sensitivity plus broad frequency coverage

Foreground S/N > 100 in each pixel and freq bin
 Spectral index uncertainty ± 0.001 in each pixel
 Dust physics to inform foreground subtraction

Spectral coverage spanning 7+ octaves

Polarized spectra from 30 GHz to 6 THz
 400 channels to fit 15 free parameters
 Foreground noise penalty only 2%



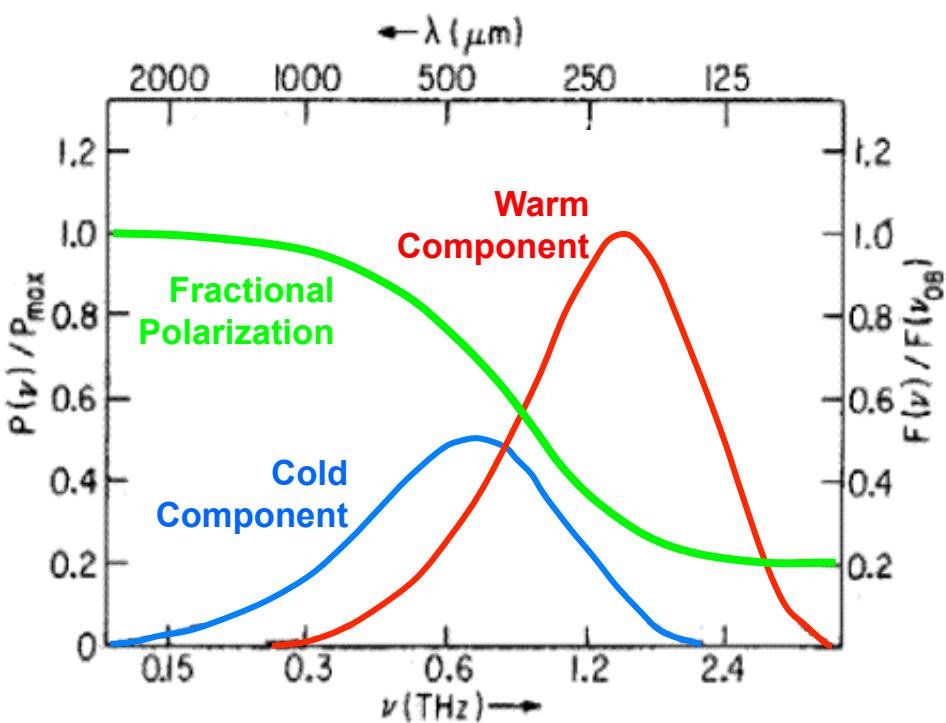
Foreground Science



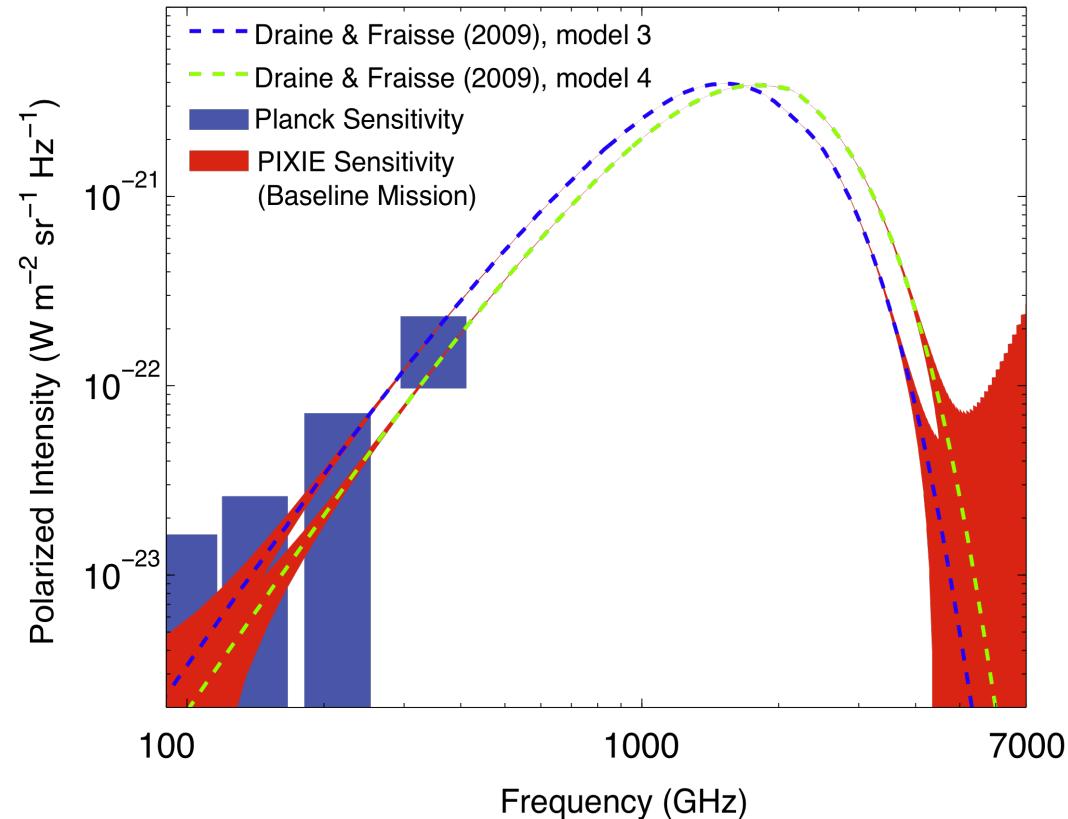
Polarization depends on composition

- Silicate: Colder, More polarized
- Carbonaceous: Warmer, Less polarized

Sensitive probe of dust composition



Hildebrand & Kirby 2004



PIXIE data from 30 GHz to 6 THz

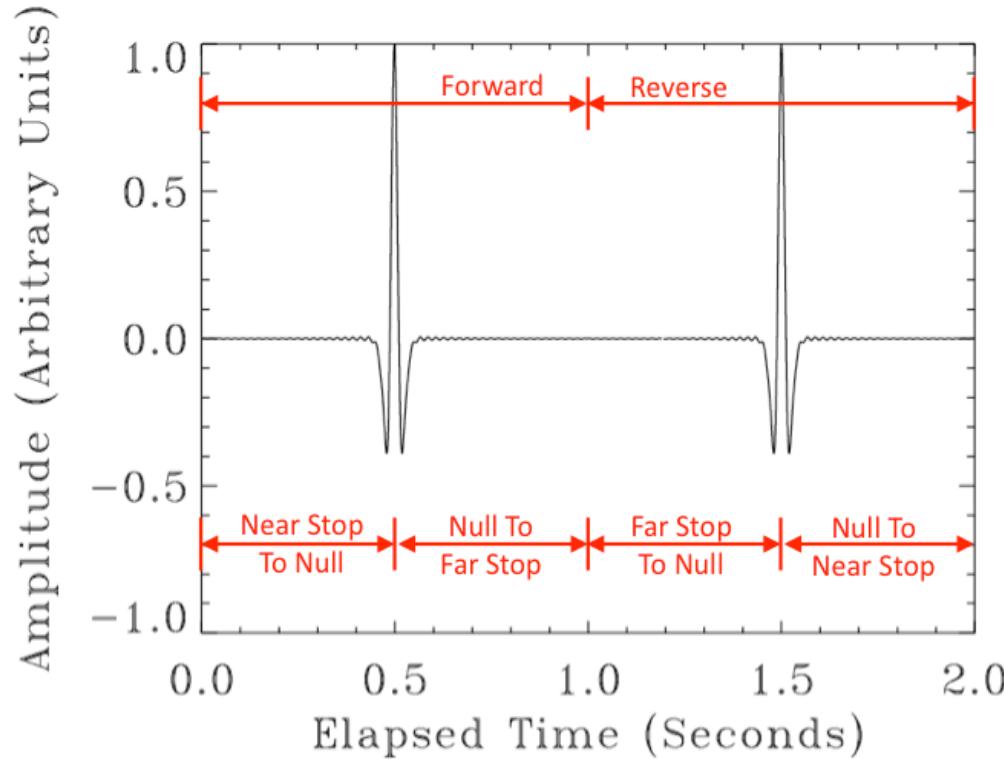
- Temperature(s)
- Fractional polarization
- Chemical composition

Constrain dust properties for each line of sight



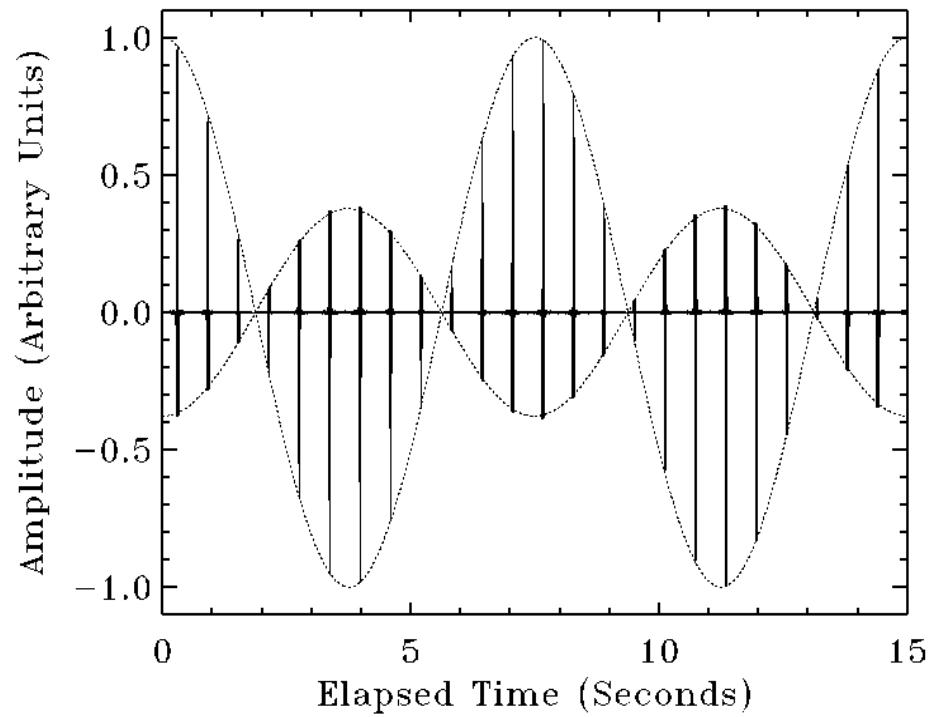
Systematic Error Control

Multiple Instrumental Symmetries



Spacecraft spin imposes amplitude modulation of entire fringe pattern

Same information 4x per stroke with different time/space symmetries



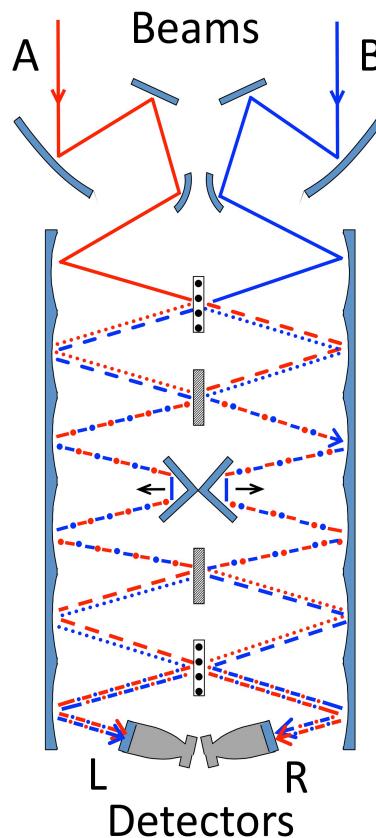
Multiple Redundant Symmetries Allow Clean Instrument Signature

Systematic Error Budget

Efficient suppression of potential systematic errors



Symmetry	Mitigates
x vs y Polarization	Beam/pointing
Left vs Right Detector	Beam/pointing
A vs B Beam	Differential loss
Real vs Imaginary FFT	1/f noise, relative gain



$$P_{Lx} = \frac{1}{2} \int (E_{Ay}^2 + E_{Bx}^2) + (E_{Bx}^2 - E_{Ay}^2) \cos(z\omega/c) d\omega$$

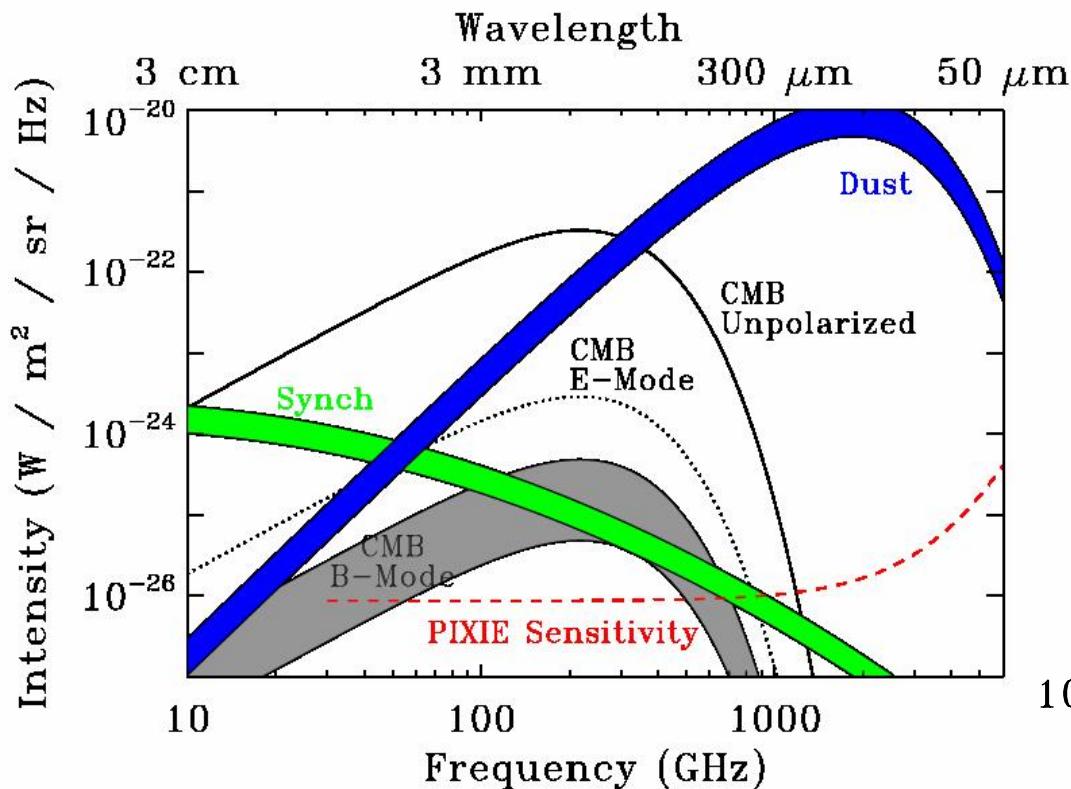
$$P_{Ly} = \frac{1}{2} \int (E_{Ax}^2 + E_{By}^2) + (E_{By}^2 - E_{Ax}^2) \cos(z\omega/c) d\omega$$

$$P_{Rx} = \frac{1}{2} \int (E_{Ax}^2 + E_{By}^2) + (E_{Ax}^2 - E_{By}^2) \cos(z\omega/c) d\omega$$

$$P_{Ry} = \frac{1}{2} \int (E_{Ay}^2 + E_{Bx}^2) + (E_{Ay}^2 - E_{Bx}^2) \cos(z\omega/c) d\omega$$

Effect	Leakage	PIXIE Mitigation						(nK)
		FTS	Spin	Orbit	XCal	Symmetry	Preflight	
Cross-polar beam	E→B		✓			✓	✓	1.5
Beam ellipticity	∇²T→TB		✓	✓		✓	✓	2.7
Polarized sidelobes	ΔT→B		✓	✓		✓	✓	1.1
Instrumental polarization	ΔT→B		✓	✓	✓	✓	✓	<0.1
Polarization angle	E→B			✓		✓	✓	0.7
Beam offset	ΔT→B		✓	✓	✓	✓	✓	0.7
Relative gain	ΔT→B	✓			✓	✓		<0.1
Gain drift	T→B	✓			✓	✓		<0.1
Spin-synchronous emission	ΔT→B	✓	✓		✓	✓	✓	<0.1
Spin-synchronous drift	T→B	✓			✓	✓	✓	<0.1

Unique Science Capability



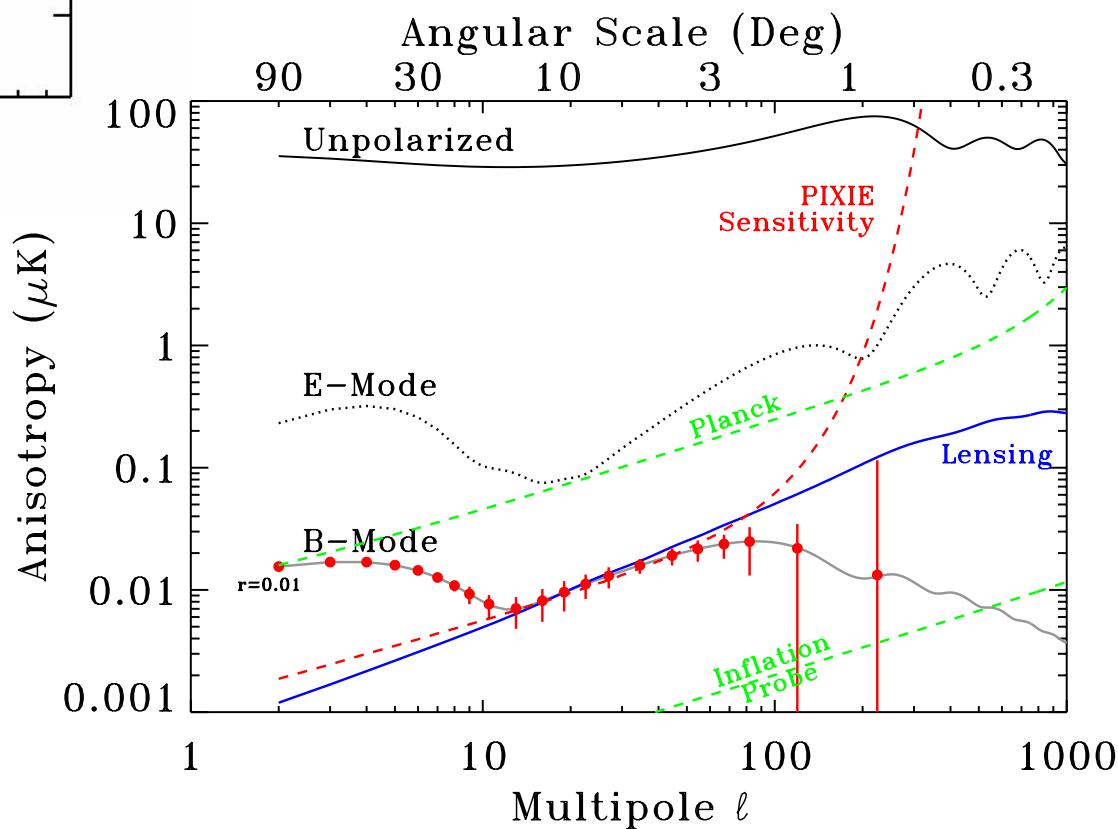
Multiple Science Goals

- Inflation/GUT Physics
- Reionization/First Stars
- CIB/Star Formation History
- ISM and Dust Cirrus

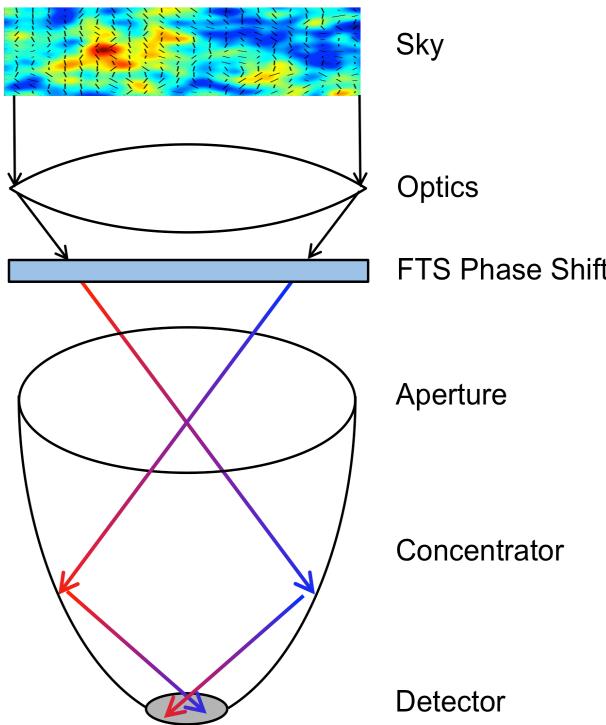
B-mode limit: $r < 0.001$ at 5σ

Full-Sky Spectro-Polarimetric Survey

- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each $0.9^\circ \times 0.9^\circ$
- Pixel sensitivity $6 \times 10^{-26} \text{ W m}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$
- CMB sensitivity 70 nk RMS per pixel



Design Trades (No Free Lunch)



PIXIE Multi-Moded
Optics

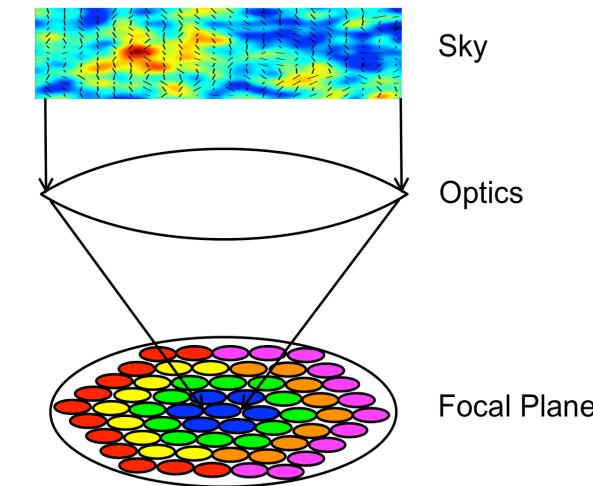
Penalties

Concentrator vs Focal Plane Array
Angular Resolution (x6 at 2 mm)

FTS vs Bandpass Filters
Noise (x2)

Advantages

- Fewer Detectors (x1000)
- More Frequency Channels (x25)
- Broader Frequency Range (x8)
- Smaller Cold Area (x500)



Single-Moded Focal
Plane

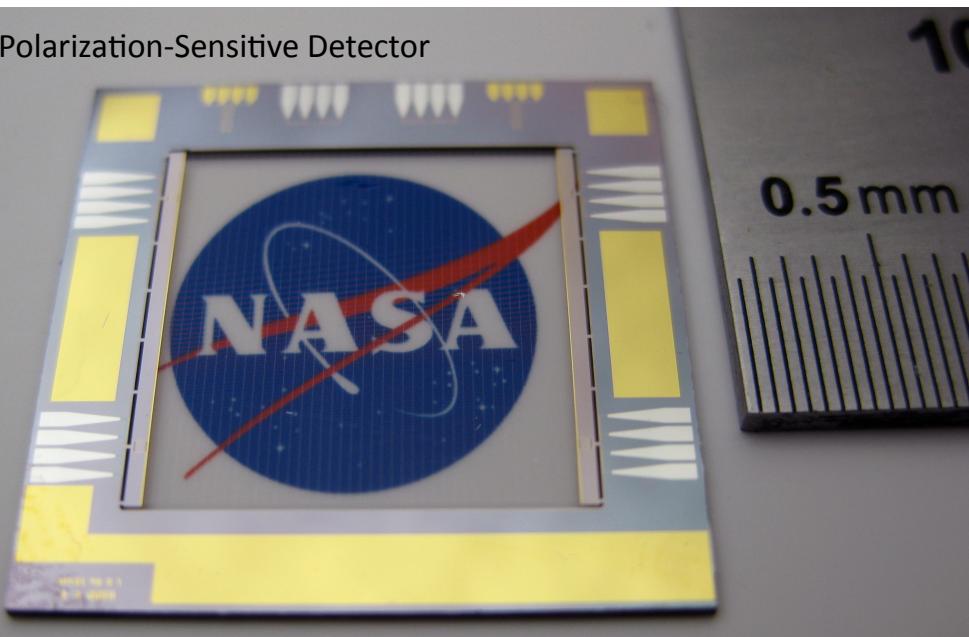
Plus: Absolute spectra provide “insurance” against possible B-mode null result

PIXIE Technology

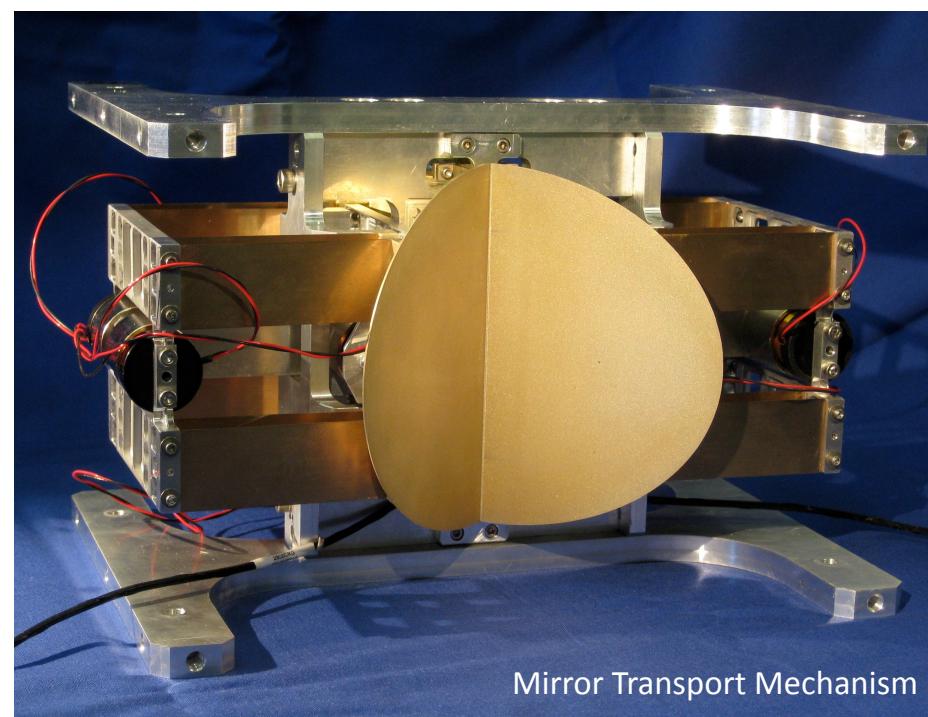
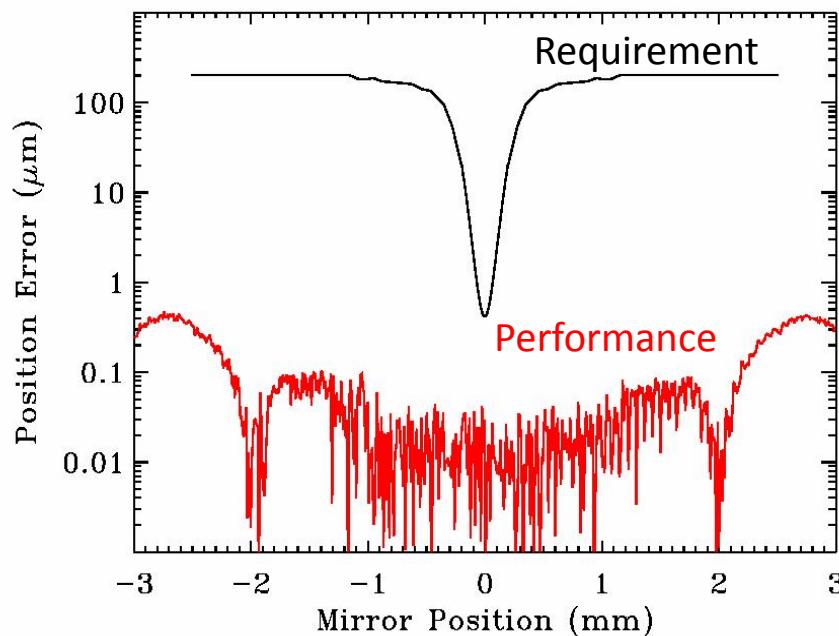
Technologically Mature Implementation



Polarization-Sensitive Detector



Parameter	Design	
Area	160 mm ²	
Fill Fraction	11%	
Frame Temperature	100 mK	
Absorber Temperature	140 mK	
Requirement	Performance	Requirement
NEP (W Hz ^{-1/2})	<10 ⁻¹⁶	0.7 x 10 ⁻¹⁶
Time Constant (ms)	<4	1
Cross-Pol at 150 GHz	<1%	0.1%



PIXIE Status



Proposed to 2011 Explorer AO

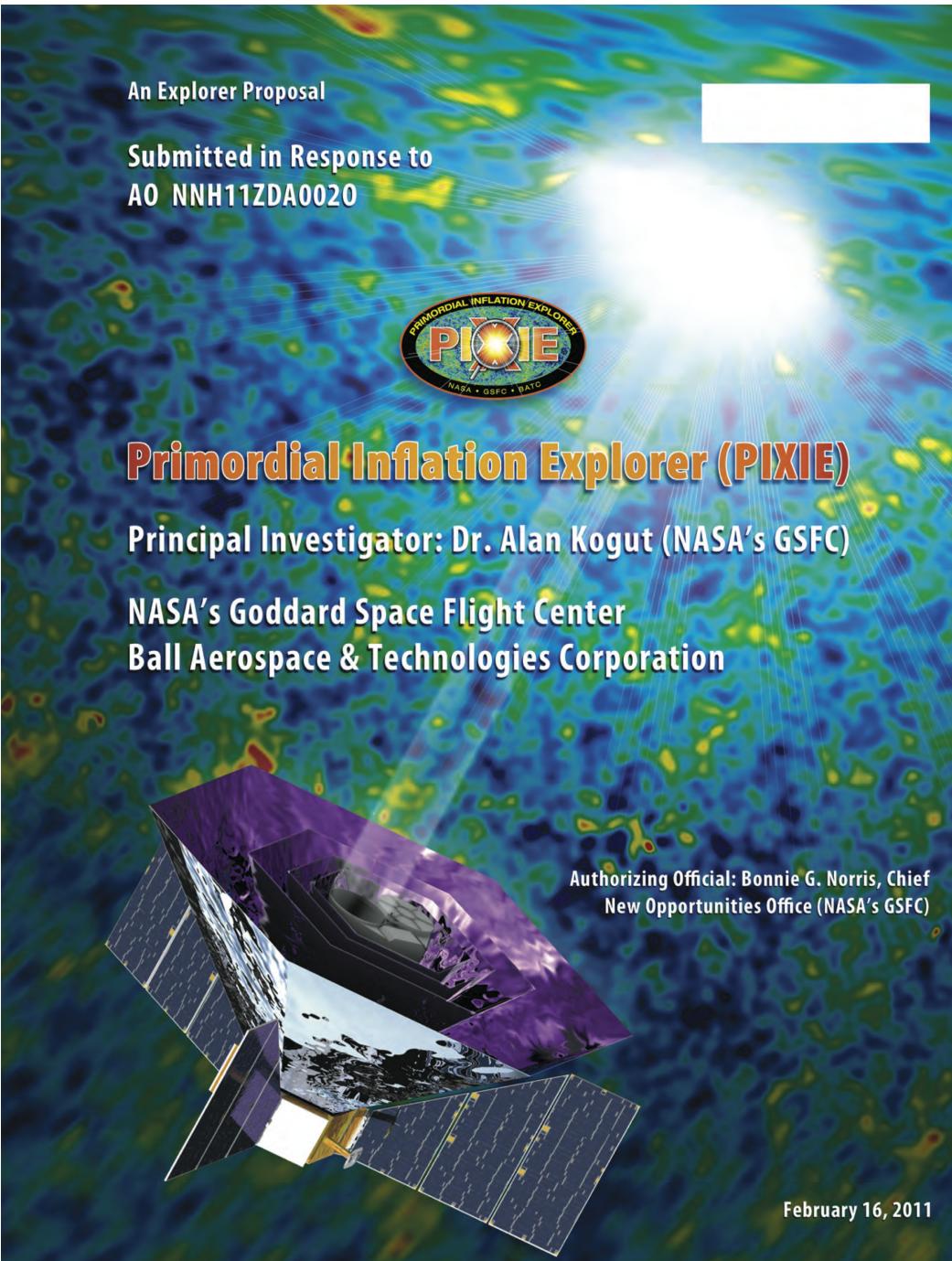
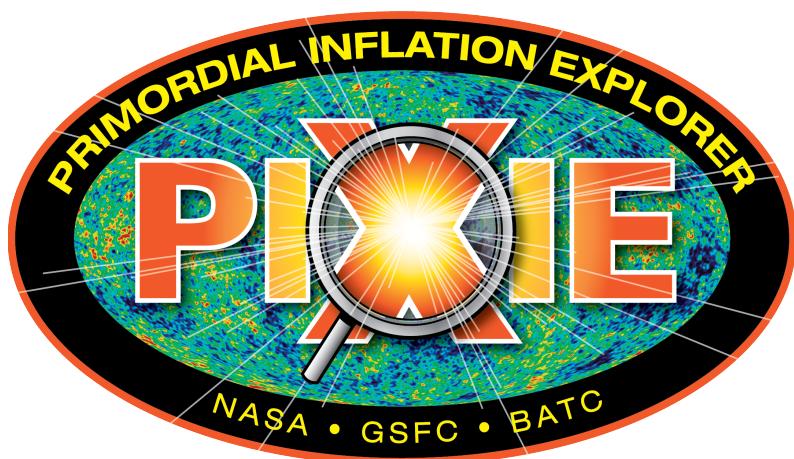
- \$200M Cost Cap + launch vehicle
- 22 full missions

PIXIE not selected; urged to re-propose

- Category I science rating
- Broad recognition of science appeal
- Absolute spectra “guaranteed science”

Re-propose to next full Explorer AO

- 2015 proposal for 2021 launch?



Backup Slides

Sensitivity: Background Limit the Easy Way

Big Detectors in Multi-Moded Light Bucket

$$\text{NEP}_{\text{photon}}^2 = \frac{2A\Omega}{c^2} \frac{(kT)^5}{h^3} \int \alpha\epsilon f \frac{x^4}{e^x - 1} \left(1 + \frac{\alpha\epsilon f}{e^x - 1}\right) dx$$

Photon noise $\sim (A\Omega)^{1/2}$
Big detector: Negligible phonon noise

$$\delta I_\nu = \frac{\delta P}{A\Omega \Delta\nu (\alpha\epsilon f)}$$

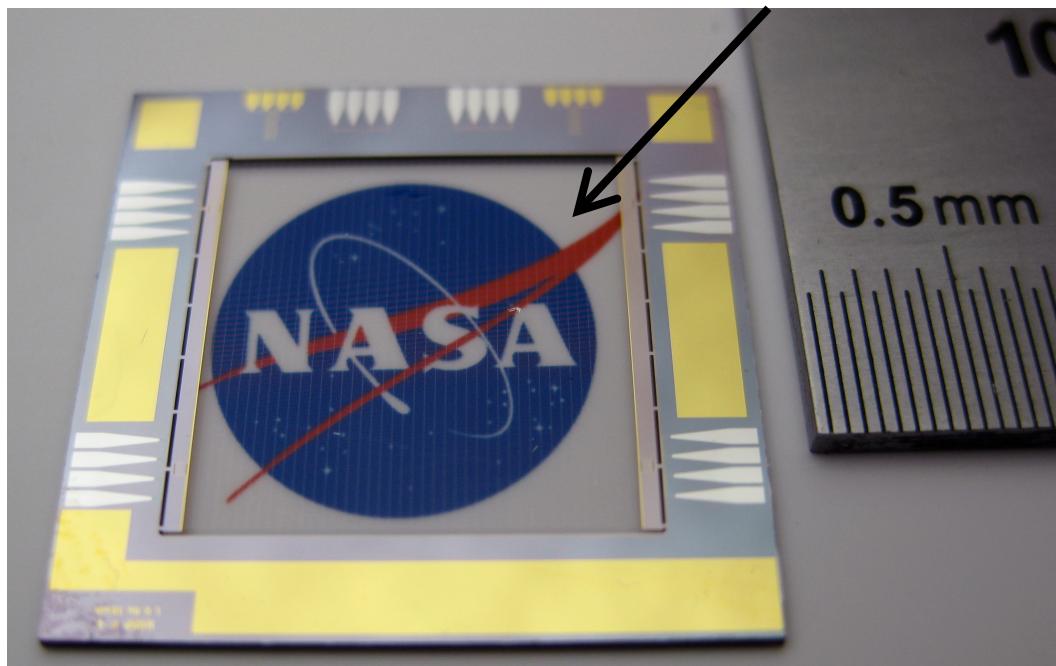
Signal $\sim (A\Omega)$
Big detector: S/N improves as $(A\Omega)^{1/2}$

PIXIE: $A\Omega = 4 \text{ cm}^2 \text{ sr}$

Parameter	Units	Calibrator Deployed	Calibrator Stowed
Stokes I (per bin)	$\text{W m}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$	2.4×10^{-22}	---
Stokes Q (per bin)	$\text{W m}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$	3.4×10^{-22}	0.5×10^{-22}
NET (CMB)	$\mu\text{K s}^{-1/2}$	13.6	---
NEQ (CMB)	$\mu\text{K s}^{-1/2}$	19.2	5.6

Sensitivity 70 nK per $1^\circ \times 1^\circ$ pixel

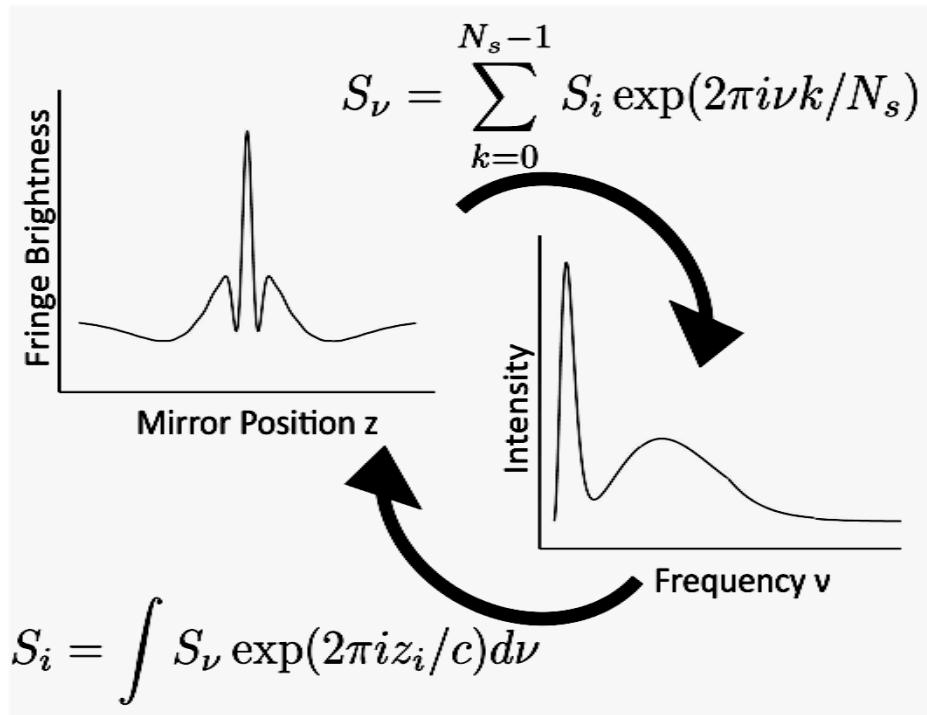
30x collecting area as Planck bolometers



PIXIE polarization-sensitive bolometer

Foregrounds : Multiple Channels the Easy Way

Fourier Transform Spectrometer



Pixel-by-pixel foreground subtraction
 400 effective channels to fit ~15 free parameters
 Spectral index uncertainty ± 0.001 in each pixel
 Continuum spectra: curvature, multiple components, ...

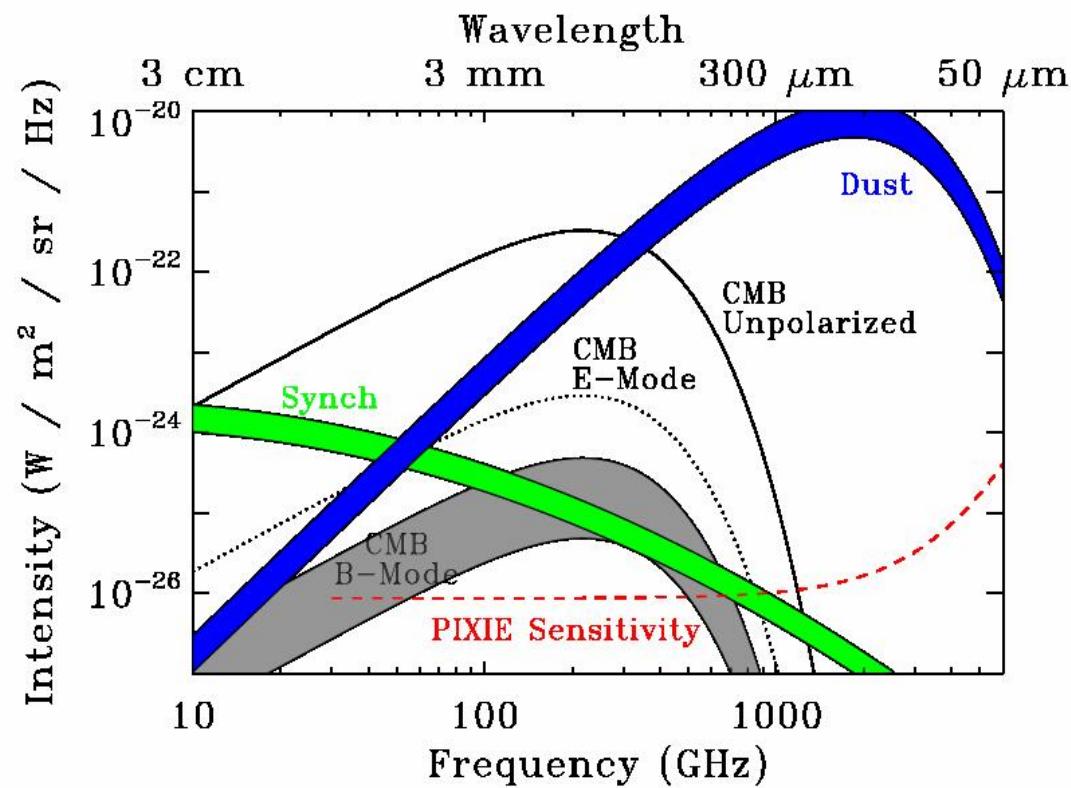
Only 2% "noise penalty" for foreground subtraction

Frequency Spectrum vs Fringe Pattern

Largest optical phase delay (1 cm) sets channel width
 Number of samples(1024) sets number of channels

PIXIE: 512 channels each 15 GHz wide

Lowest effective channel = 30 GHz (1 cm)
 Highest effective channel ~ 6 THz (50 μ m)



PIXIE Fourier Transform



Phase delay L sets channel width

$$\Delta\nu = c/L$$

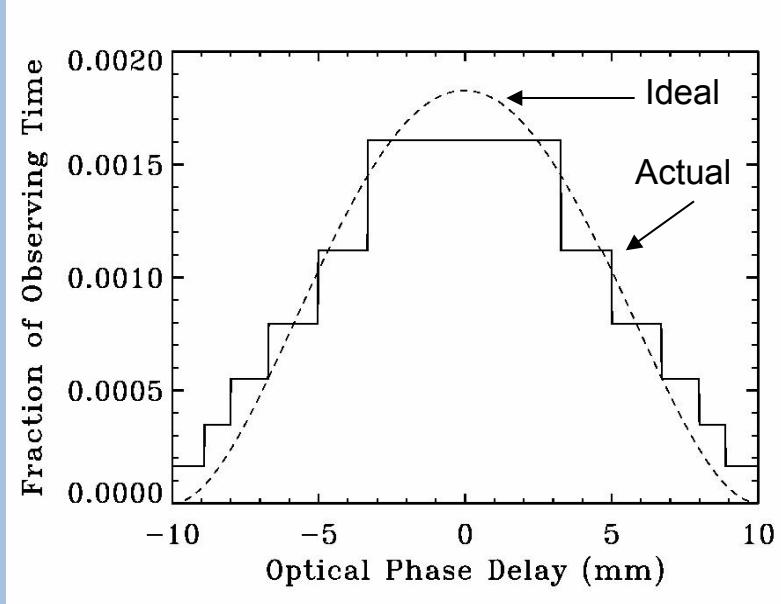
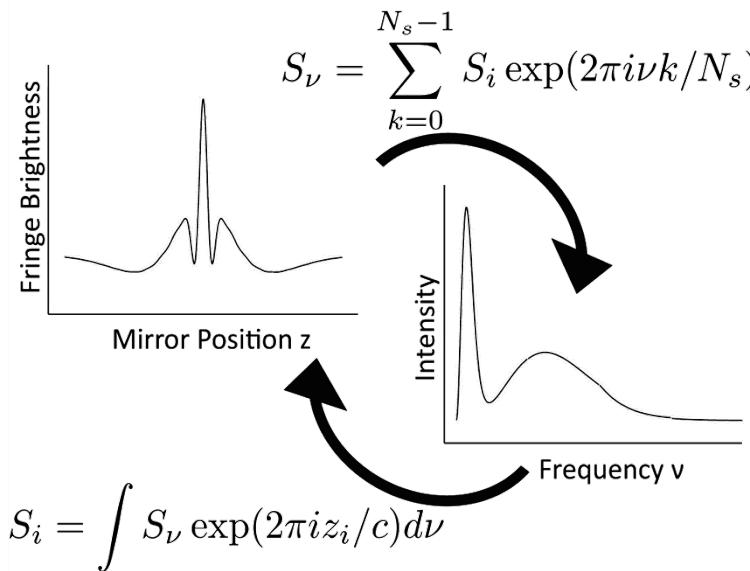
Number of samples sets frequency range

$$N_{\text{chan}} = N_{\text{samp}} / 2$$

PIXIE: ~400 usable channels

$$\Delta\nu = 15 \text{ GHz}$$

30 GHz to 6 THz (1 cm to 50 μm)



Optical Delay	Physical Stroke	Samples per Stroke	Strokes per Spin
±10 mm	±2.5 mm	1024	8
±8.9 mm	±2.3 mm	910	9
±8.0 mm	±2.1 mm	819	10
±6.7 mm	±1.7 mm	683	12
±5.0 mm	±1.3 mm	512	16
±3.3 mm	±0.9 mm	341	24

Vary stroke length to apodize Fourier transform

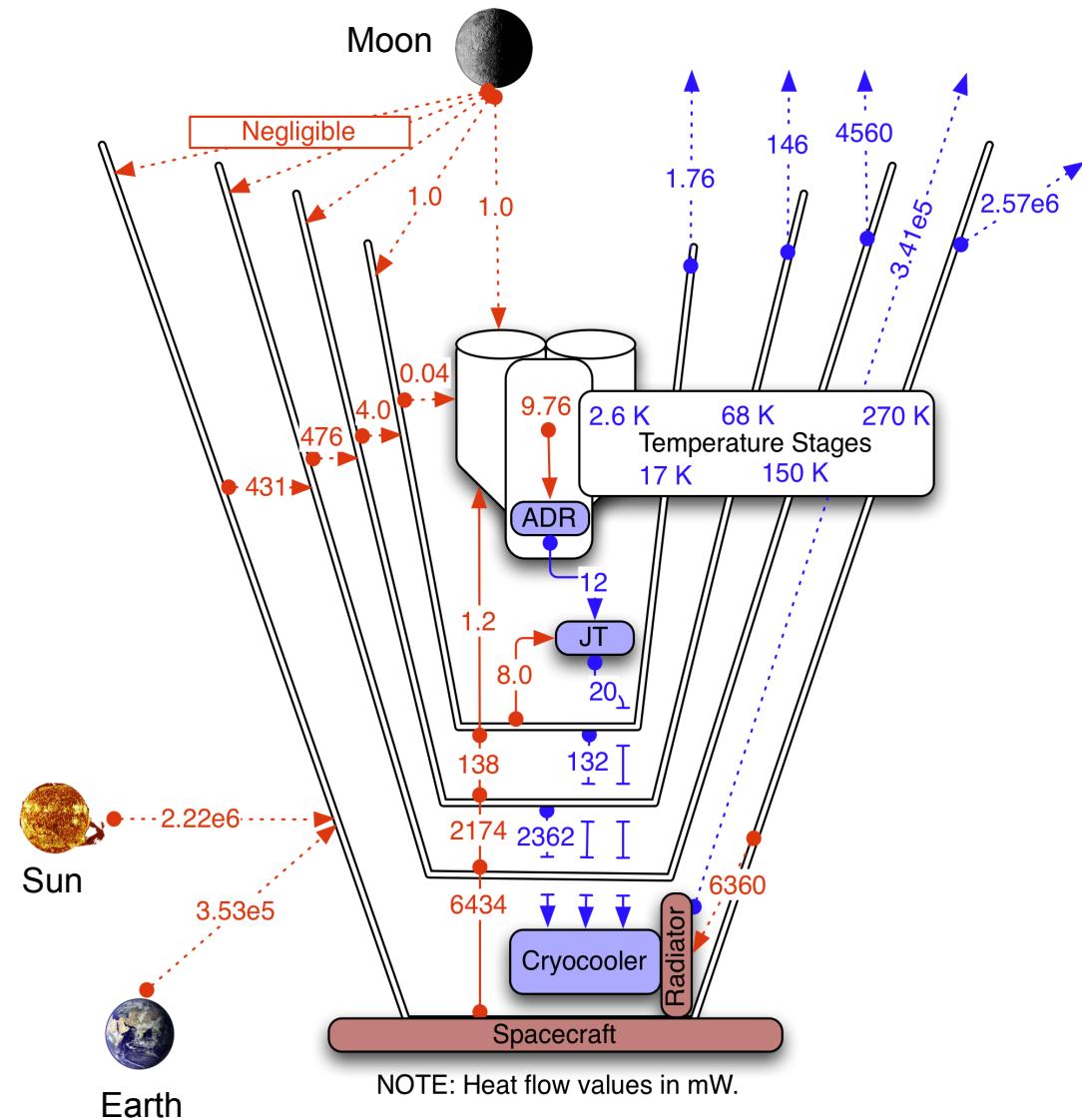


Cryogenic Budget

Layered Hybrid For Maximum Efficiency

- Thermal Shields: Cooling at 150K
- Cryocooler: Cooling at 68, 17, and 4.5K
- ADR: Cooling at 2.6 and 0.1 K

Cooler Stage	Stage Temp (K)	CBE Loads (mW)	Derated Capability (mW)	Contingency & Margin (%)
Stirling (Upper Stage)	68	2362	4613	95%
Stirling (Lower Stage)	17	132	278	111%
Joule-Thomson	4.5	20	40	100%
iADR	2.6	6	12	100%
dADR	0.1	0.0014	0.03	2043%



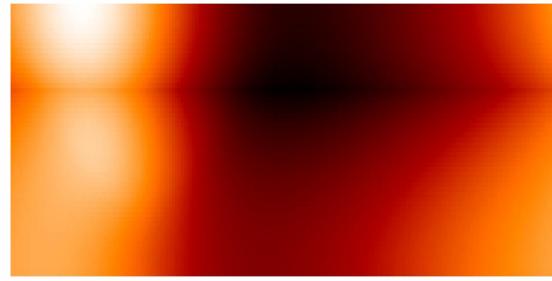
Cryogenics



Moonshine Thermal Gradient

Barrel Azimuth

Barrel Height



0.0 — 2.0 mK

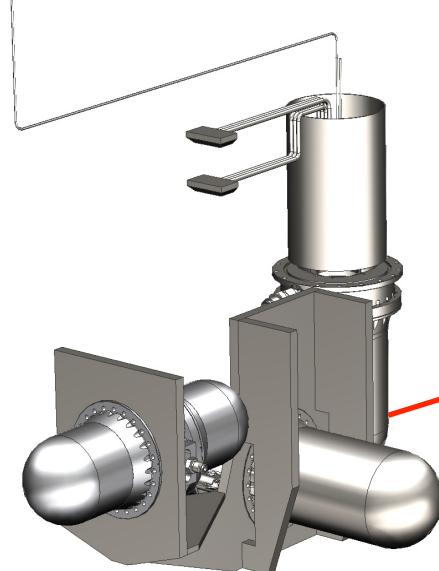
ADR (2.7 K)

ADR (0.1 K)

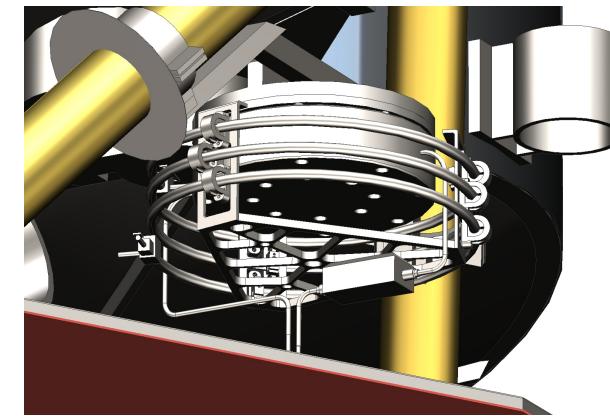
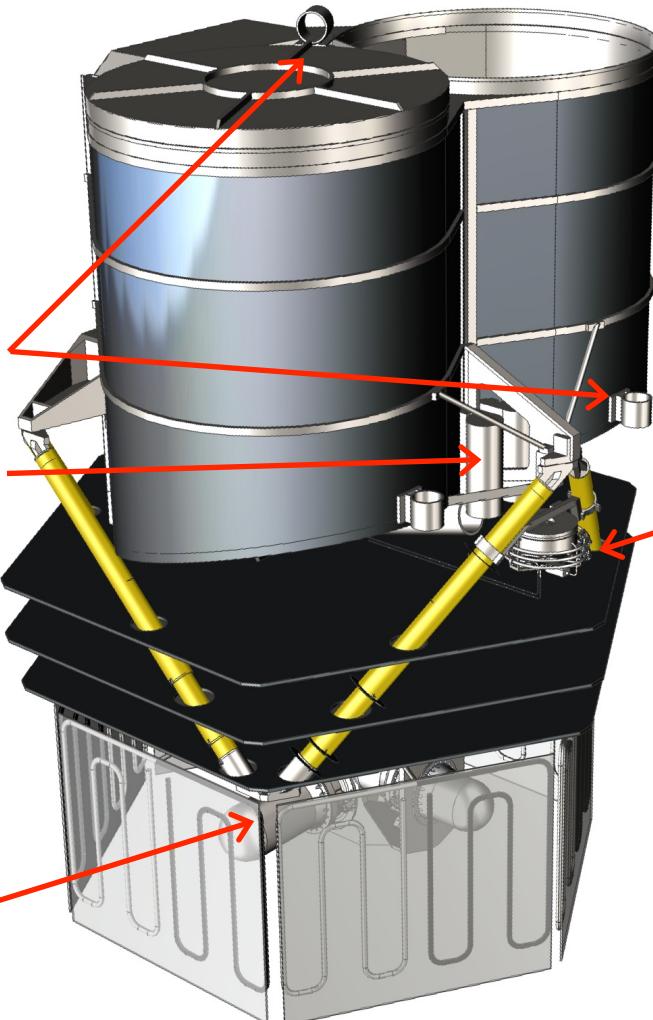
17 K Break

68K Break

150K Break



Cryo-Cooler Compressor (280 K)



J-T Cold Head (4.5 K)

Multi-Stage Cryogenic Design

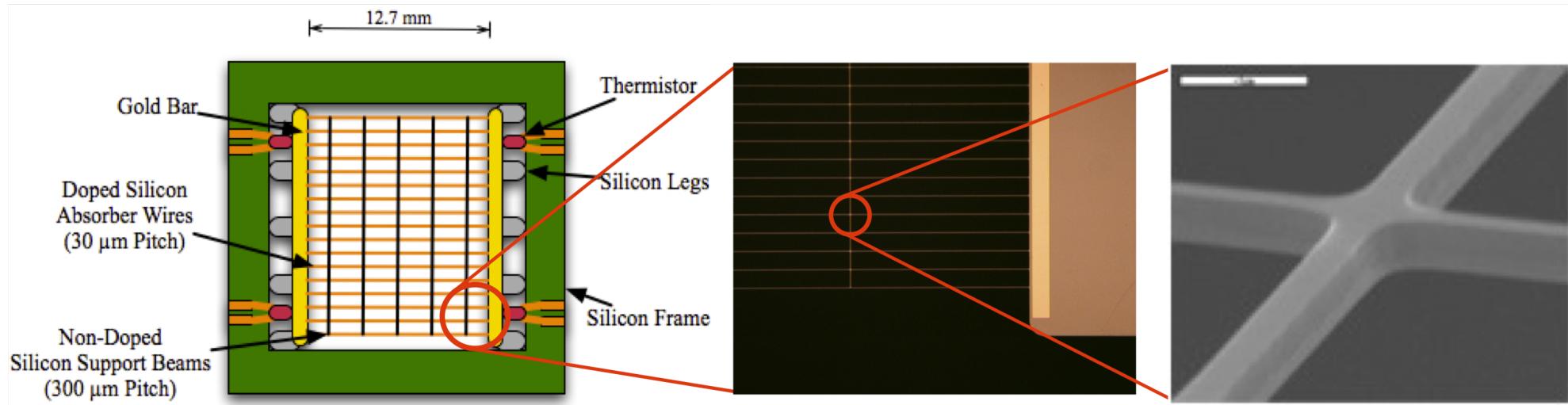
- Passive Sun Shades (not shown)
- 4.5 K Cryo-cooler
- 2.7 K ADR
- 0.1 K ADR

Thermal Lift Budget

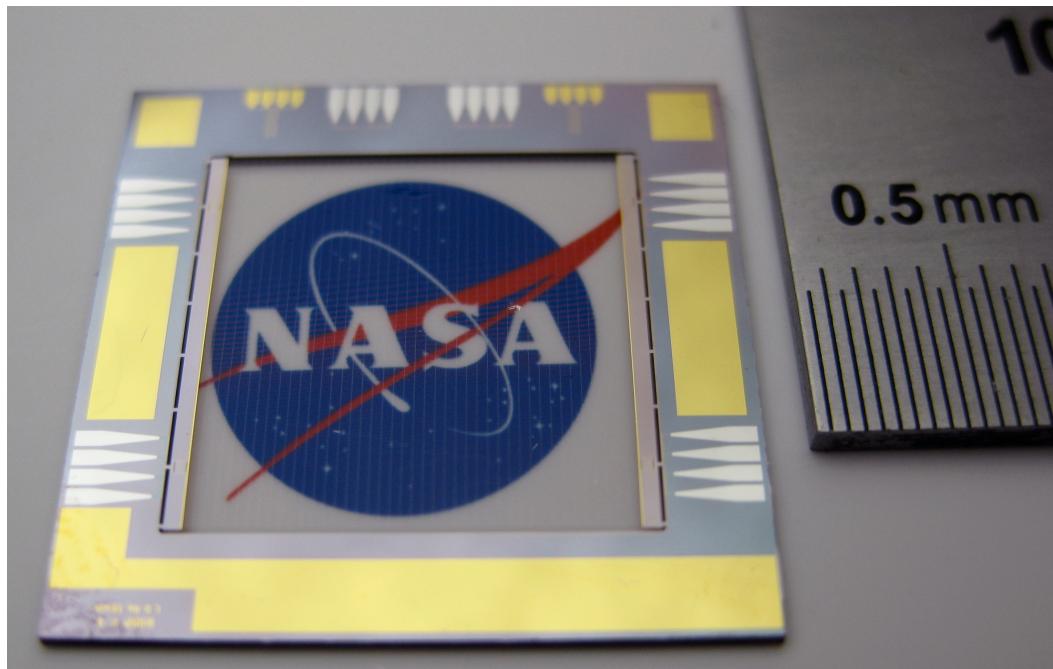
Cooler Stage	Stage Temp (K)	CBE Loads (mW)	Derated Capability (mW)	Contingency & Margin
Stirling (Upper)	68	2362	4613	95%
Stirling (Lower)	17	132	278	111%
Joule-Thomson	4.5	20	40	100%
ADR	2.6	6	12	100%
ADR	0.1	0.0014	0.03	2043%



Polarization-Sensitive Detectors

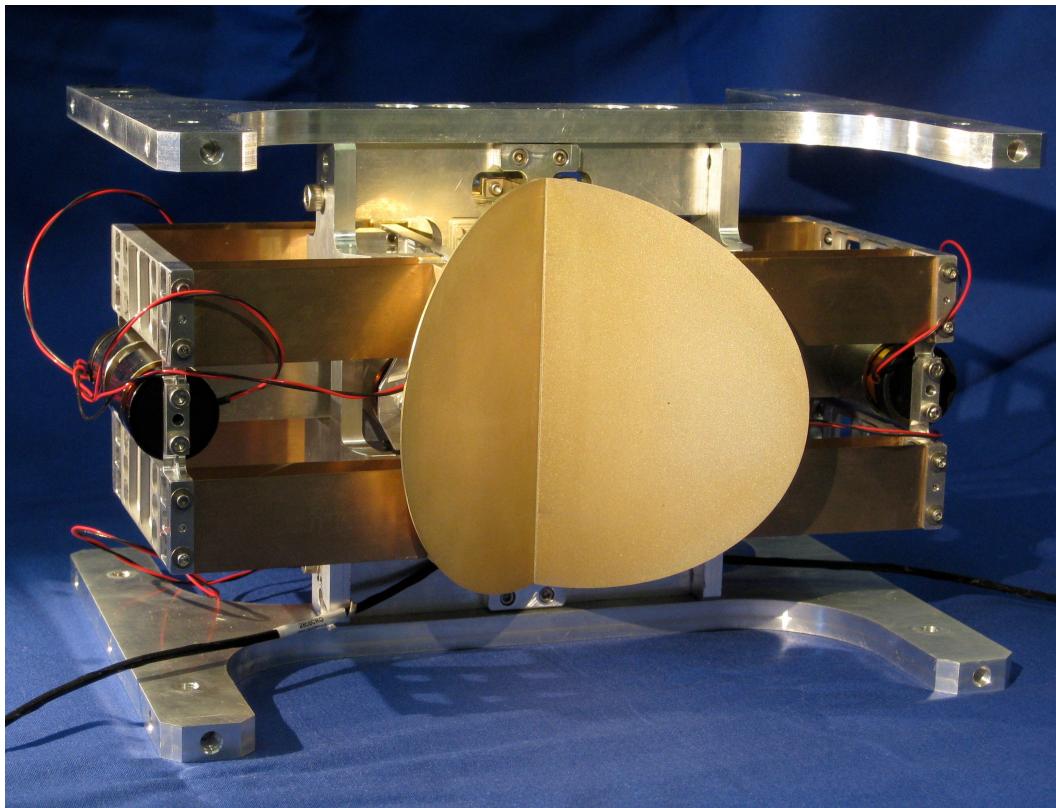


Parameter	Design	
Area	160 mm ²	
Fill Fraction	11%	
Frame Temperature	100 mK	
Absorber Temperature	140 mK	
Requirement		Performance
NEP (W Hz ^{-1/2})	<10 ⁻¹⁶	0.7 x 10 ⁻¹⁶
Time Constant (ms)	<4	1
Cross-Pol at 150 GHz	<1%	0.1%





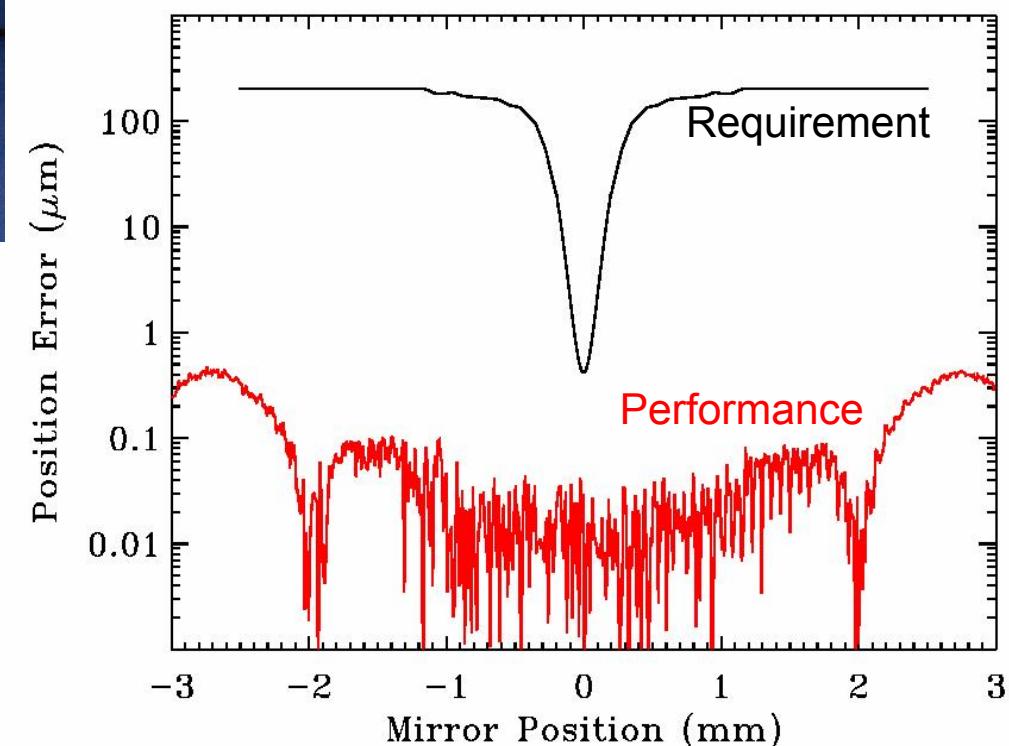
Mirror Transport Mechanism



Engineering prototype

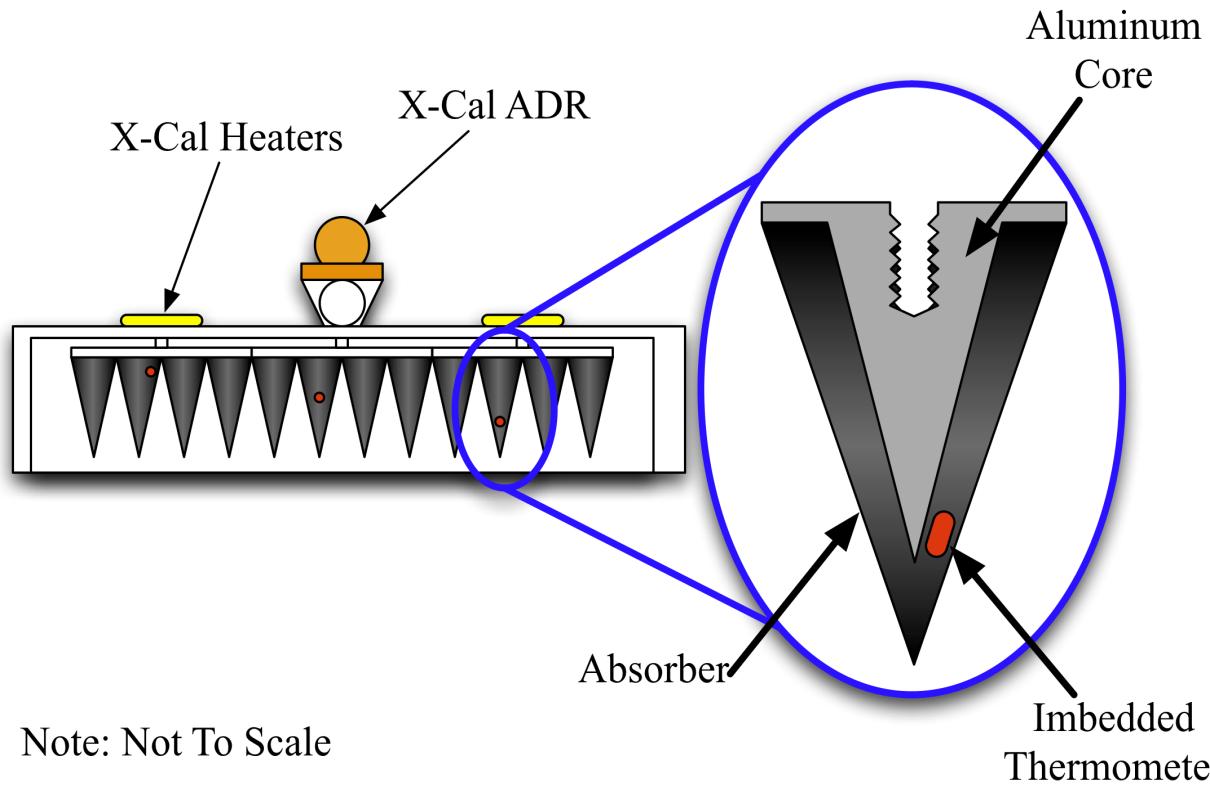
Demonstrated performance
exceeds requirement by factor of ten

Translate ± 2.54 mm at 0.5 Hz
Optical phase delay ± 1 cm
Repeatable cryogenic position



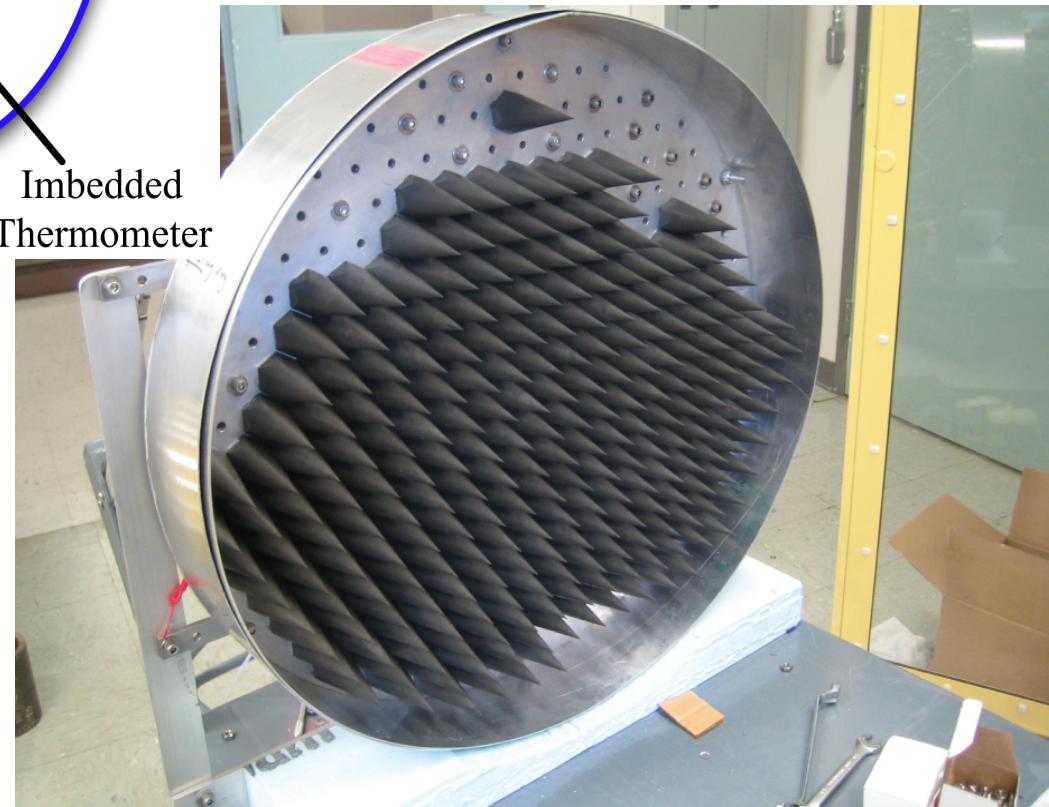


Blackbody Calibrator



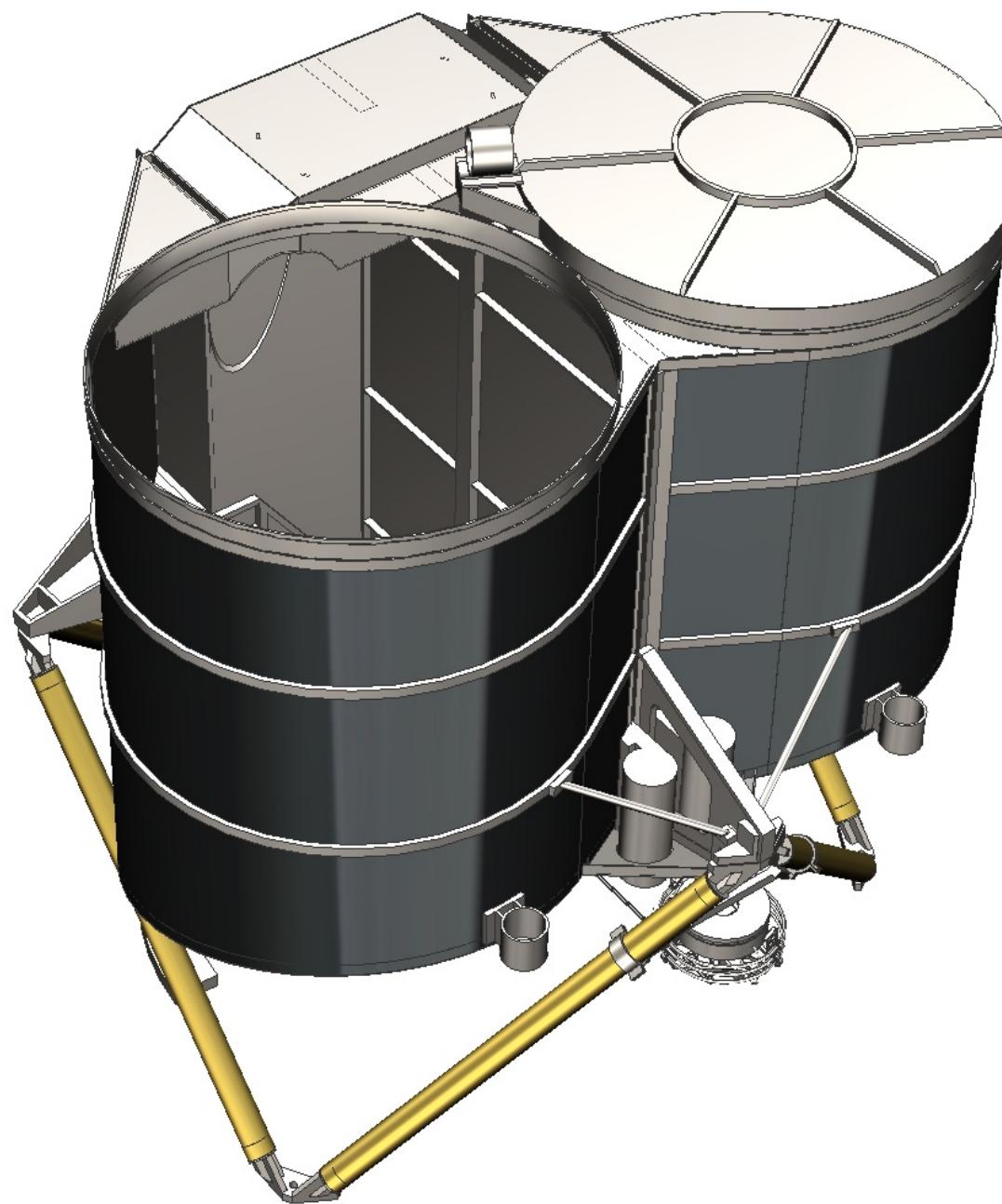
Note: Not To Scale

Based on successful
ARCADE calibrator

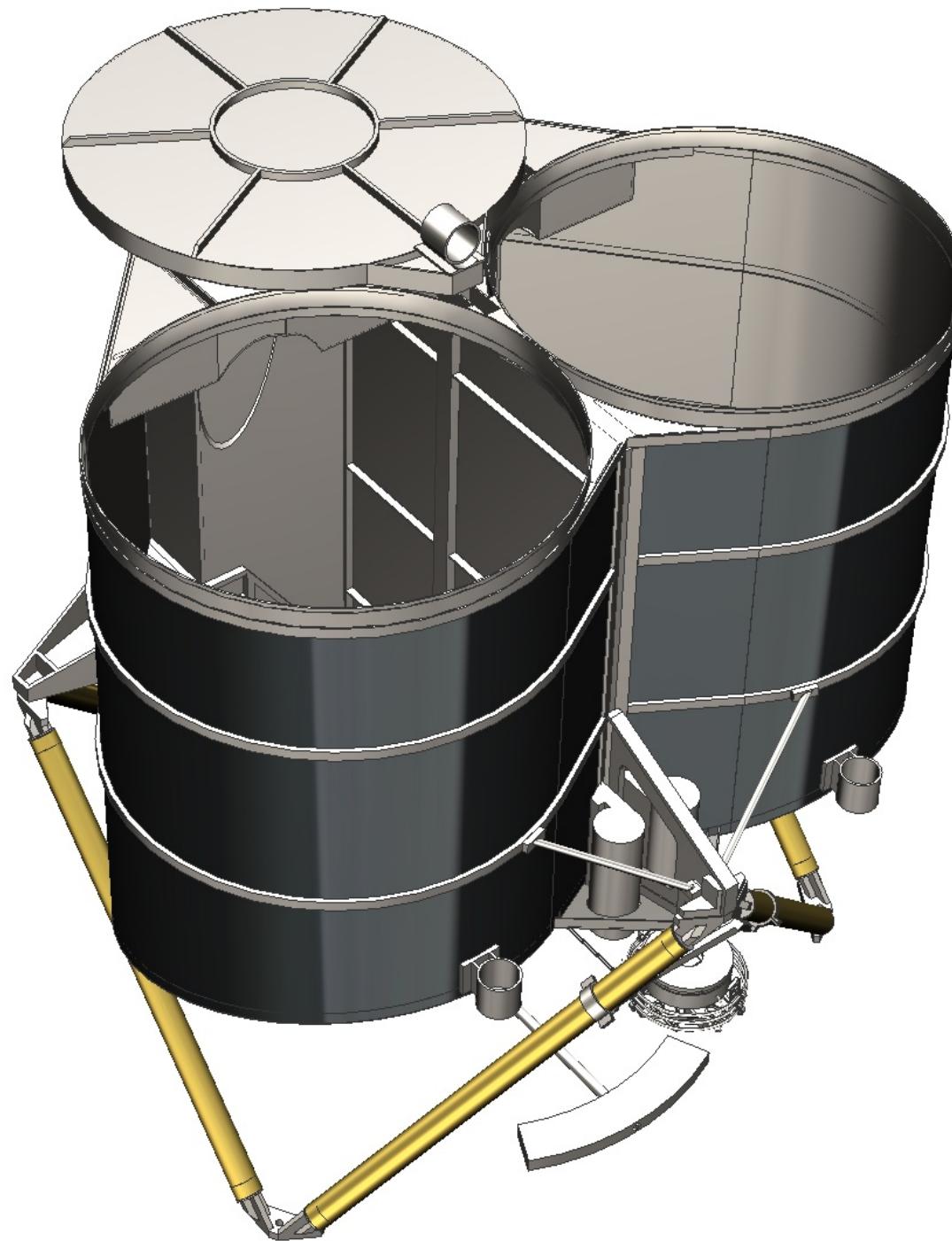


XCal Requirements		
Parameter	Requirement	Performance
Blackness (30 to 300 GHz)	< -60 dB	-65 dB
Blackness (> 300 GHz)	< -20 dB	-50 dB
Temperature Range (Body)	2.6 - 3.5 K	2.6 - 3.5K
Temperature Range (Single Cone)	2.6 - 20 K	2.6 - 20 K
Temperature Gradient	< 3 μ K	< 1 μ K

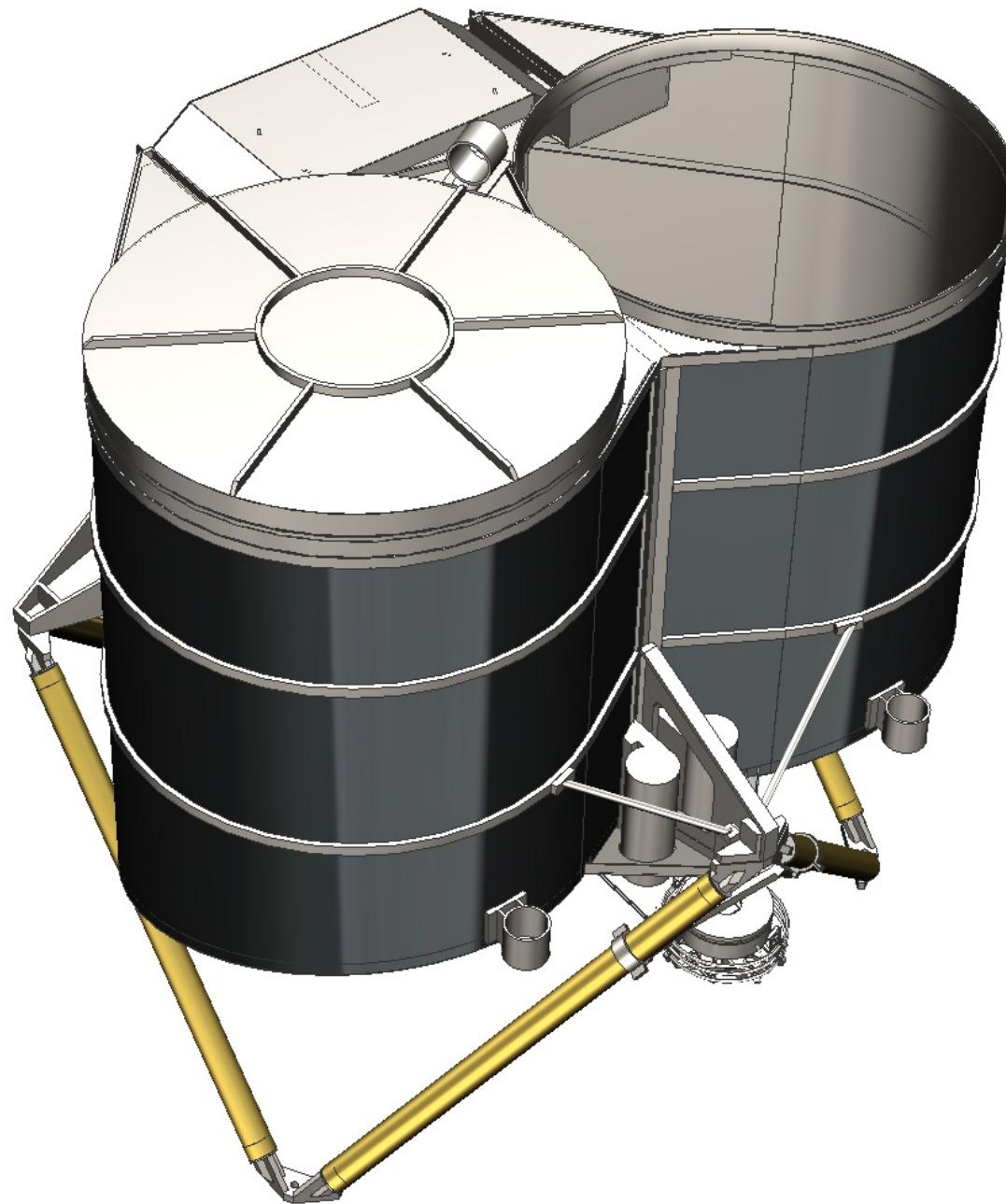
External Calibrator



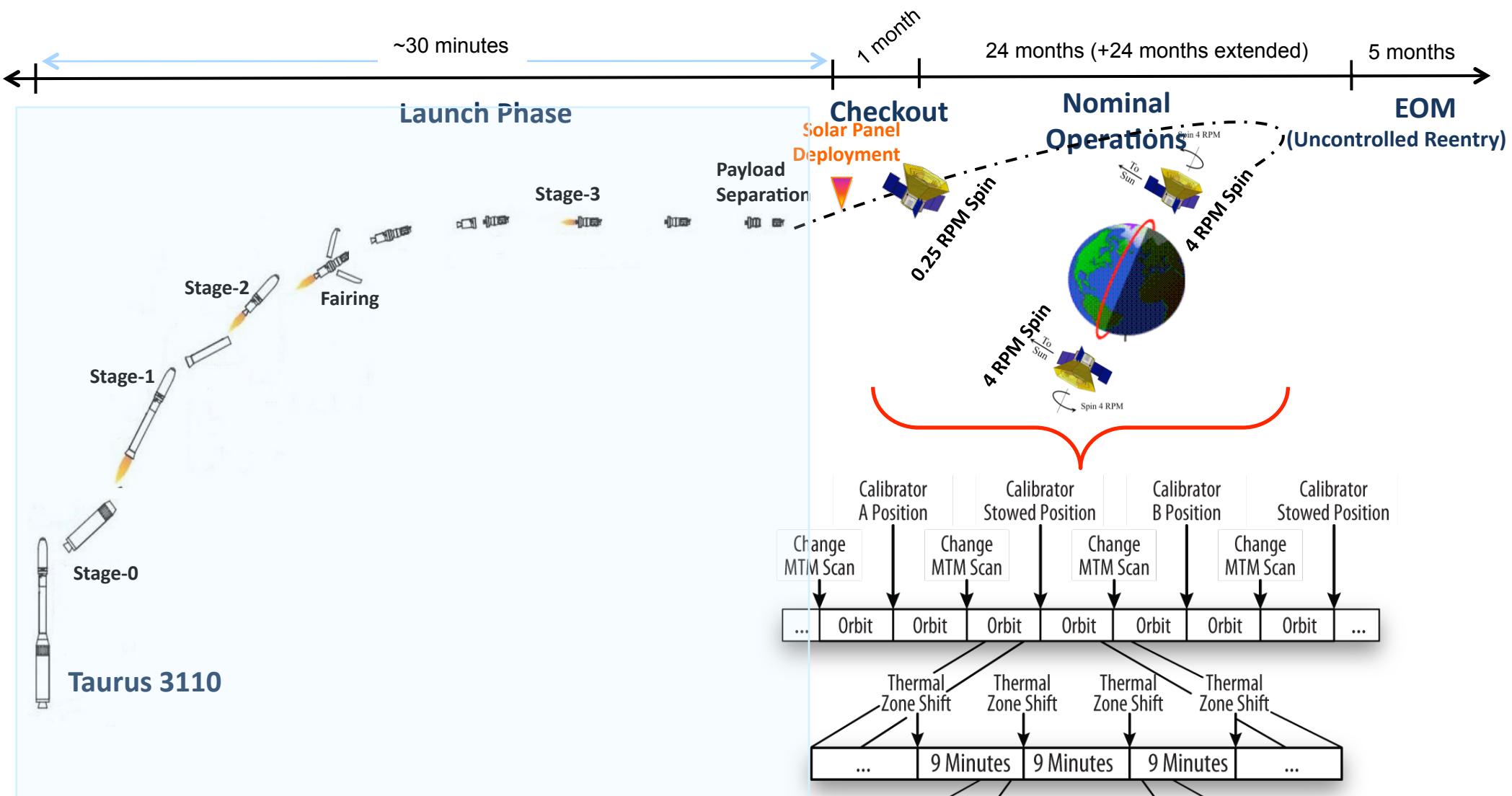
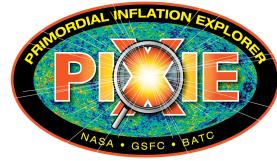
External Calibrator



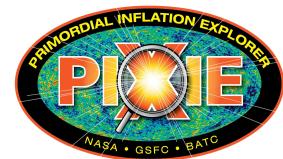
External Calibrator



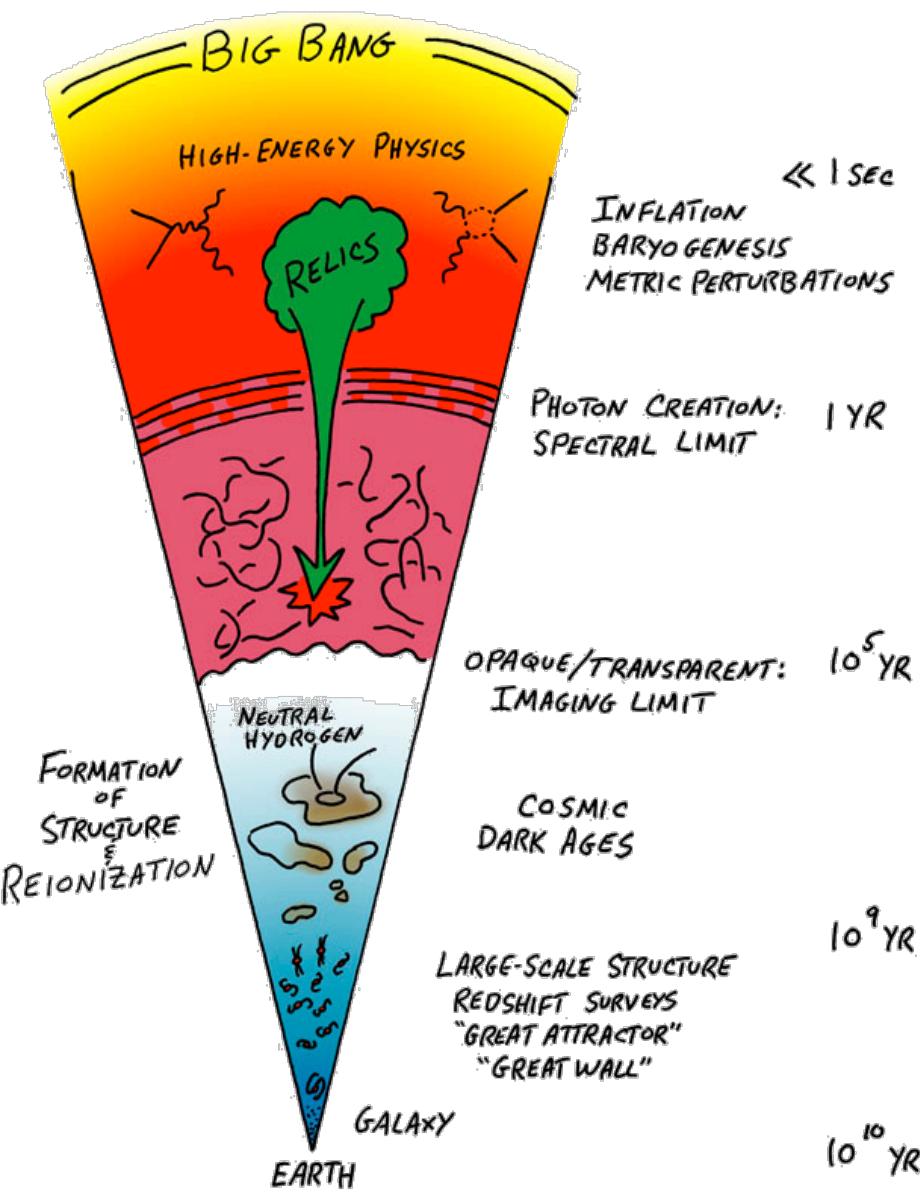
Mission Operations



Simple table-driven operations
“Spin and Stare” science



PIXIE Samples Cosmic History



Big Bang Cosmology *

Inflation
GUT physics
Quantum gravity

Primary Science

Early Universe

Dark matter decay/annihilation
Primordial density perturbations

Secondary Science

Reionization and First Stars *

Ionization history at end of Dark Ages
Nature of first stars

Large-scale Structure

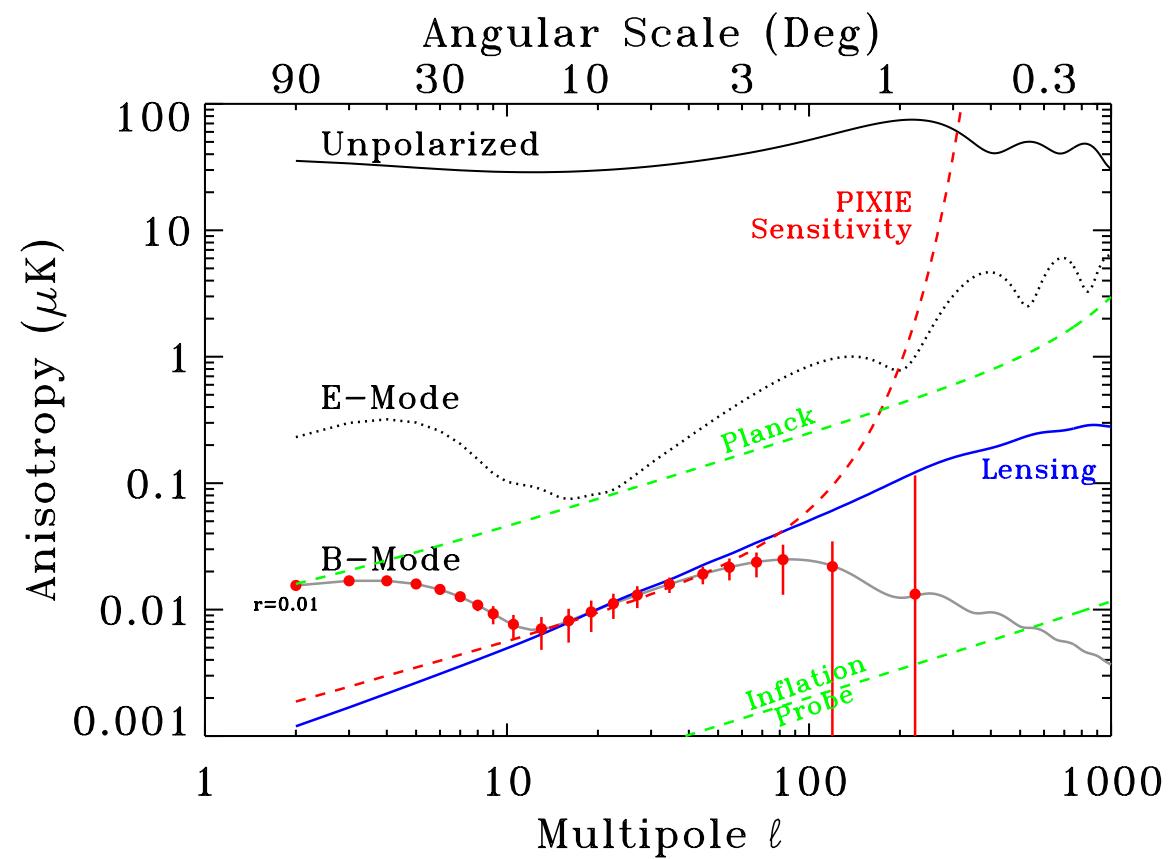
Galaxy bias vs dark matter density
Star formation at redshift 2–3

Galactic Structure

Assembly history of the Galaxy
Dust & chemical separation

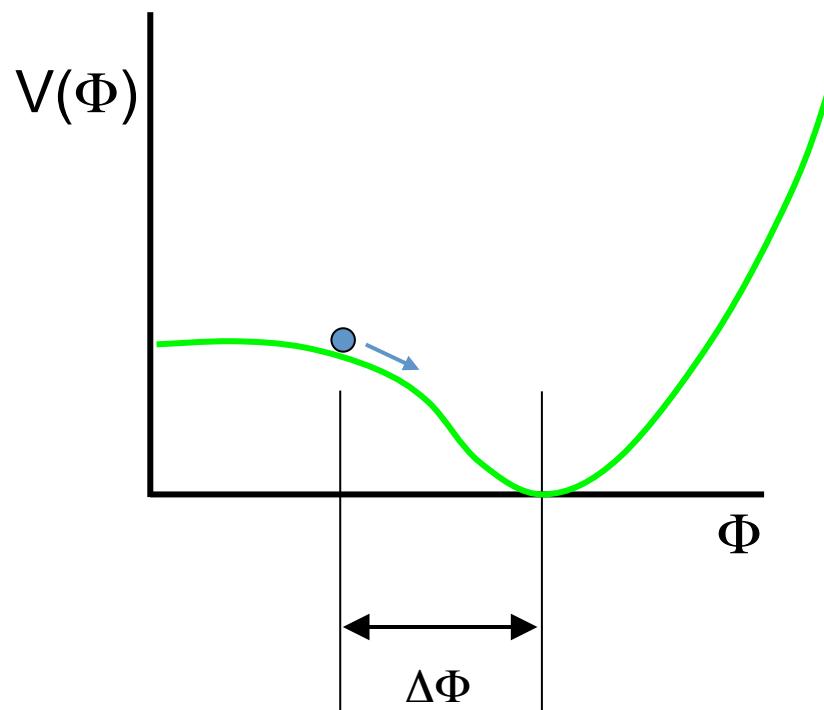
* Specifically called out in Astro-2010 Decadal Survey

Primary Science: Inflation



GUT-Scale Physics: $r < 10^{-3}$ at 5σ

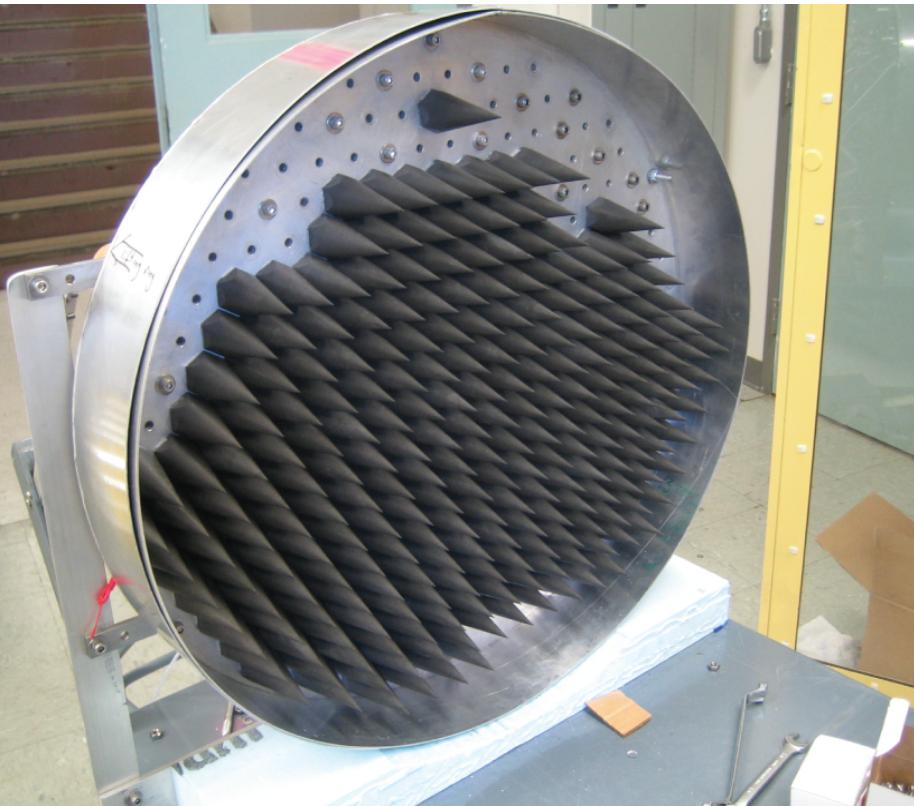
- Detect ~all large-field models
- Power spectrum to $\ell \sim 100$
- Reach limit of lensing foreground



Planck-Scale Physics: Map B-Mode Polarization

- Consistency relation $r = -6.2 n_t$
- Statistics of B-mode polarization field

Secondary Science: Inflation

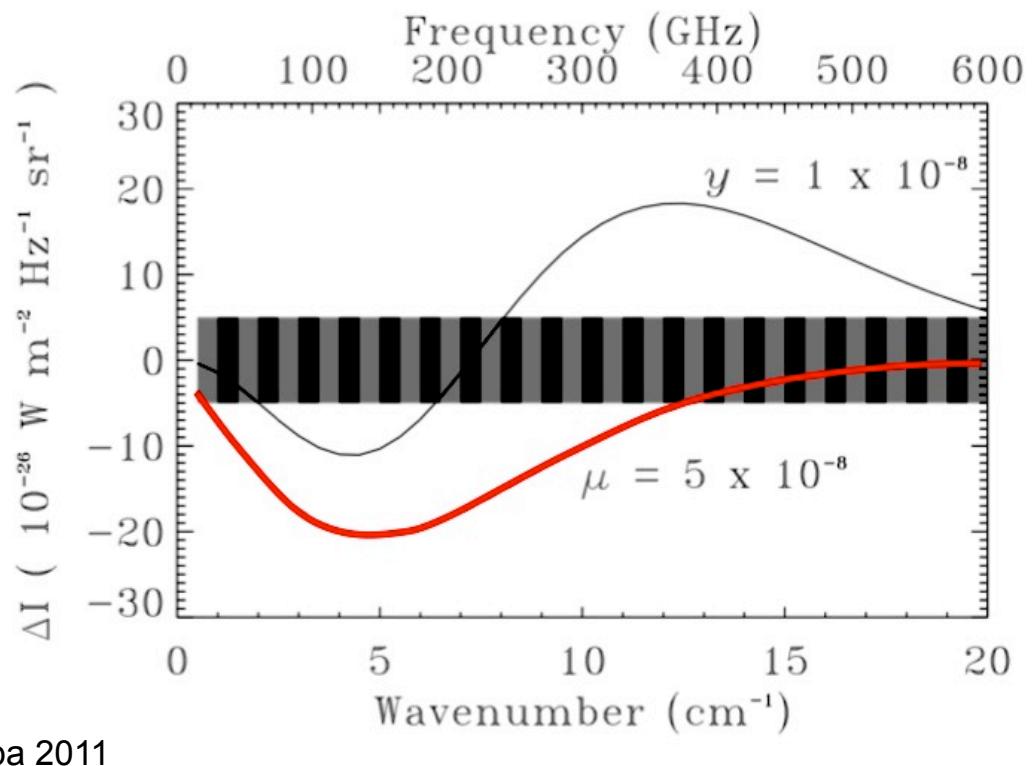


Blackbody calibrator: Spectral distortions

$$\text{Chemical potential } \mu = 1.4 \frac{\Delta E}{E}$$

Energy release at $10^6 < z < 10^8$

PIXIE limit $\mu < 10^{-8}$



Silk damping of primordial perturbations

- Scalar index n_s and running $d\ln n_s/d\ln k$
- Physical scale ~ 1 kpc ($1M_\odot$)

Daly 1991

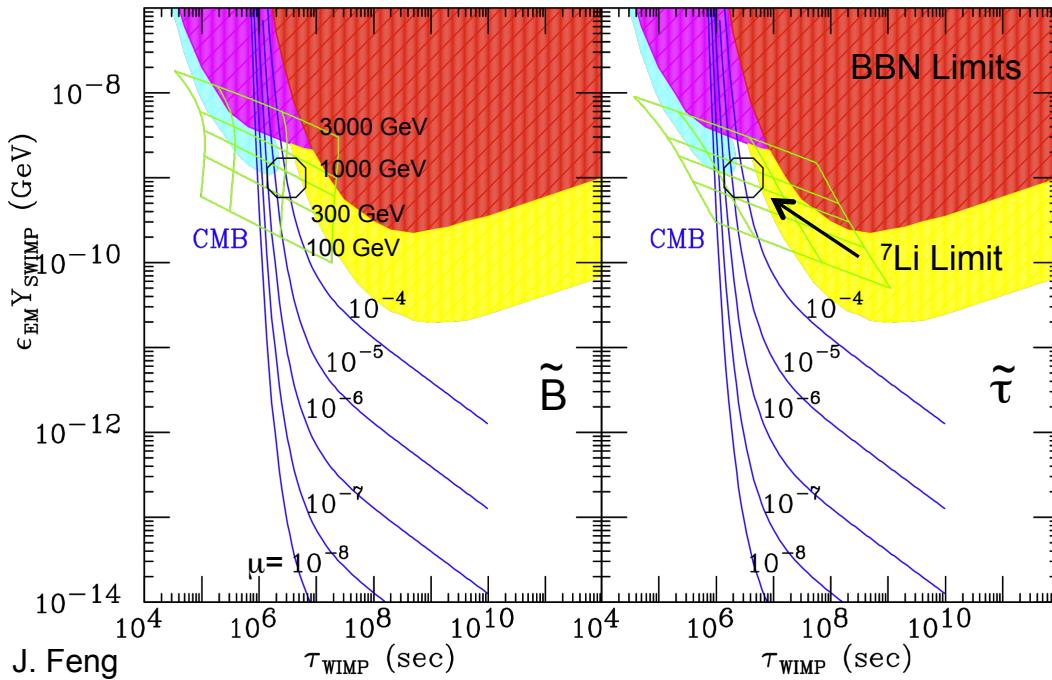
Hu, Scott, & Silk 1994

Khatri, Sunyaev, & Chluba 2011

Secondary Science: Dark Matter

Blackbody distortion from dark matter decay or annihilation

slepton decay



J. Feng

PIXIE limit $\mu < 10^{-8}$

Reach cosmological limit $\tau < 3 \times 10^6$ sec

Test of gravitino dark matter

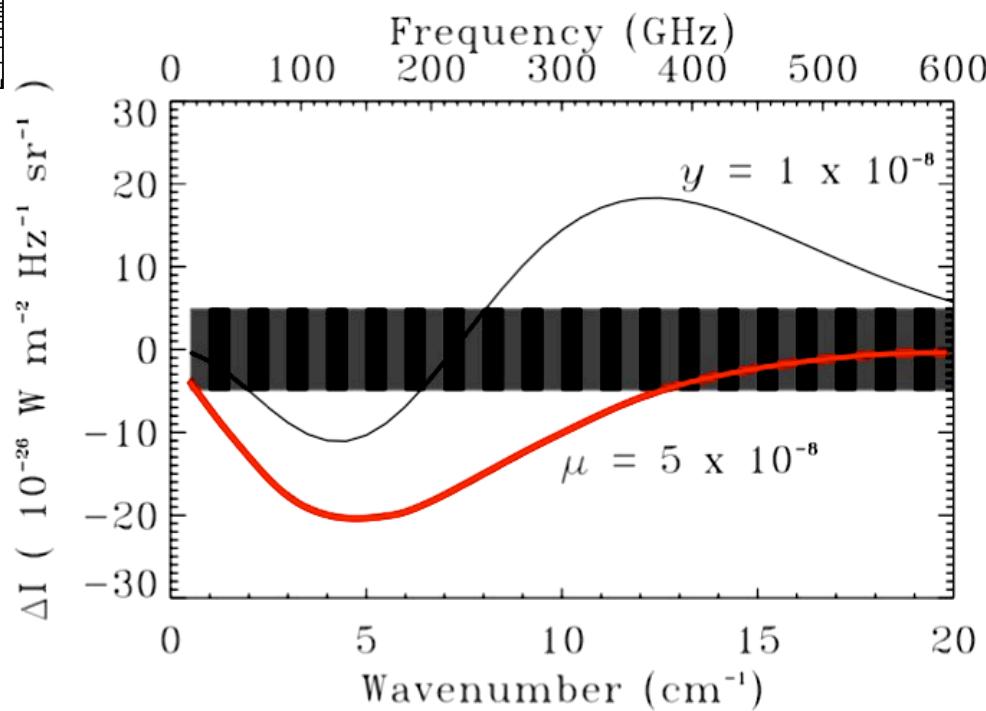
McDonald et al 2001
de Vega & Sanchez 2010
Feng 2010

Energy release at $10^6 < z < 10^8$

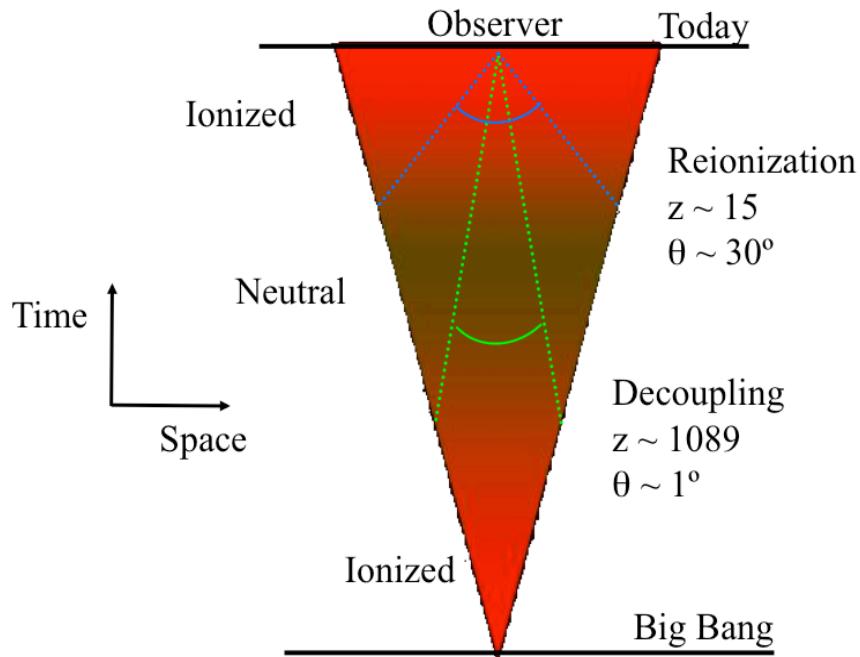
$$\text{Chemical potential } \mu = 1.4 \frac{\Delta E}{E}$$

Energy release $\Delta E \sim \Omega_{\text{DM}} \Gamma \Delta m$

Distort CMB from blackbody spectrum



Secondary Science: Reionization



Same scattering for both signals:

Combine to get $n(z)$ and T_e

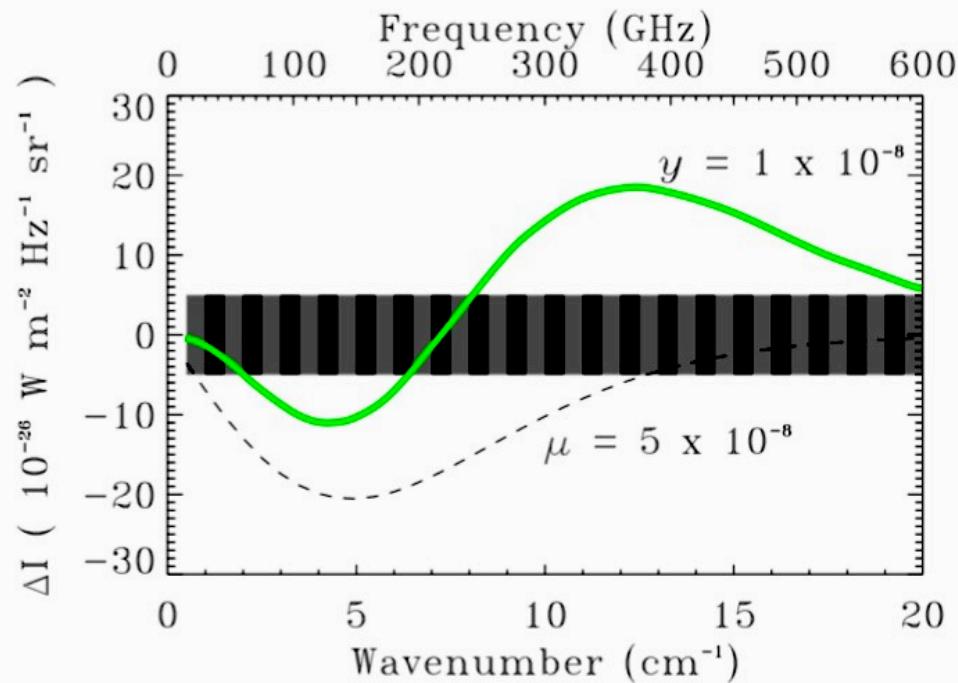
- T_e probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects

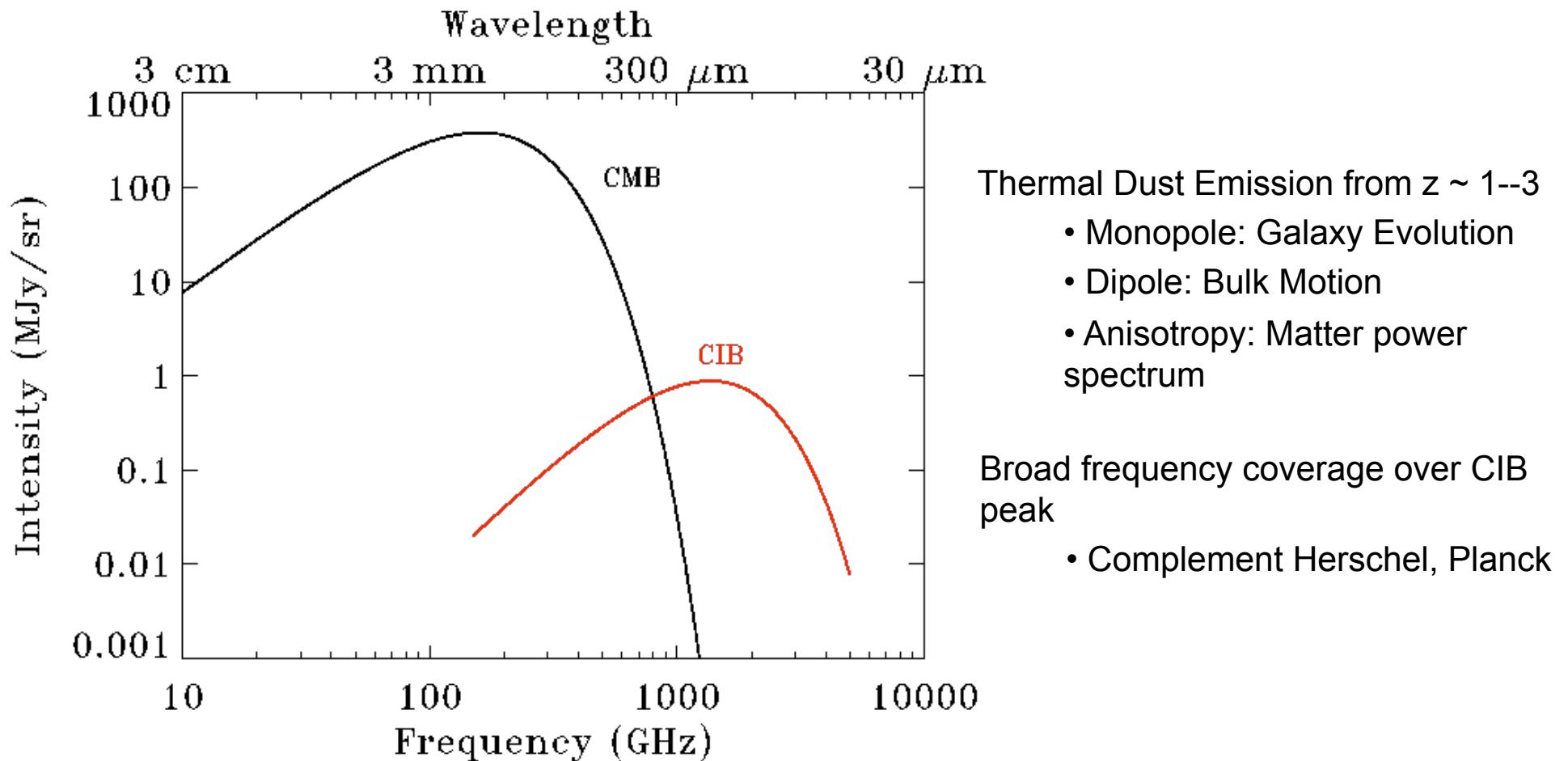
Polarization: Optical depth \sim Electron density $n(z)$

Angular scale \leftrightarrow Horizon at redshift z

Spectrum: y distortion \sim Electron pressure $\int n k T_e$
• PIXIE limit $y < 5 \times 10^{-9}$
• Distortion must be present at $y \sim 10^{-7}$



Secondary Science: Cosmic Infrared Background



Thermal Dust Emission from $z \sim 1--3$

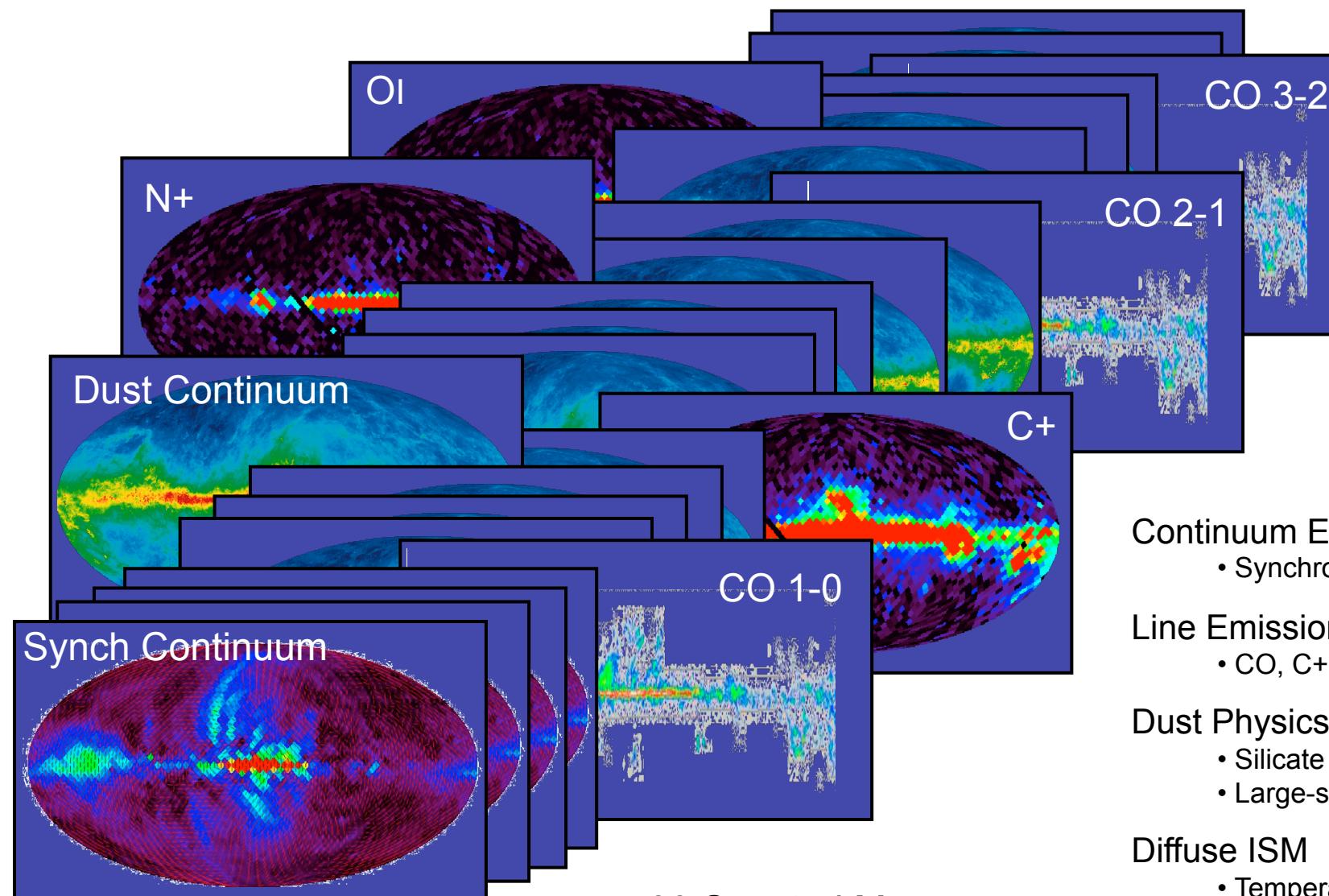
- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Matter power spectrum

Broad frequency coverage over CIB peak

- Complement Herschel, Planck

PIXIE noise is down here!

Secondary Science: Interstellar Medium



400 Spectral Maps
Stokes I, Q, U
 $\Delta\nu = 15 \text{ GHz}$

Continuum Emission
• Synchrotron, Dust

Line Emission
• CO, C+, N+, O, ...

Dust Physics
• Silicate vs carbonaceous dust
• Large-scale magnetic field

Diffuse ISM
• Temperature, Density
• Energy Balance
• Metalicity

Extremely Rich Data Set!